



Edited by
Jianshe Chen
Lina Engelen

Food Oral Processing

fundamentals of eating and
sensory perception

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Fundamentals of Eating and Sensory Perception

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Preface

'It is critically important not only what we eat but also how we eat!'

Eating, or food oral consumption, is an essential part of our daily life. It is a routine process of obtaining the energy and nutrients essentially required for living and well-being and also the appreciation of sensory pleasure and enjoyment. The eating process can be seen as the ultimate stage of the food supply chain and is the starting point of food disintegration and the digestion process. Therefore, the eating quality and sensory experience of a food always remains a top concern to food researchers, food manufacturers and retailers, as well as consumers. How a food is broken down inside the mouth could also have important implications for our well-being and health, as indicated by Horace Fletcher (1849–1919) almost a century ago. Even though the practice of eating is well-known to most, the fundamental principles involved in eating and sensory perception of food are not as obvious as they are normally perceived. This book endeavours to review the latest research findings on food oral processing and sensory perception. The main objective of the book is to provide readers with up-to-date knowledge and understanding of the underpinning principles of food physics, oral physiology and sensory psychology of an eating process.

Studies of food texture, taste, flavour, aroma and colour as independent scientific disciplines began only around the middle of the last century, shortly after food science and technology became the subject of degree courses. Knowledge of food sensory properties was in urgent demand due to largely industrialised food manufacturing and supply, which led to huge expansions of research activities in these areas during the second half of last century. Approaches during the early stages of eating and food sensory studies were mostly either through an objective instrumental characterisation or a human subject sensory description method. For example, for food texture studies, rheology and mechanical investigations were most commonly used, where food was essentially treated as a material, that is mechanical and rheological properties (e.g. hardness, springiness, viscosity, cohesiveness, etc.) were characterised using instrumental devices, and results were interpreted in relation to sensory perception. On the other hand, food taste and aroma studies focused mainly on small molecules, their release, characterisation and detection. It is only during the last one or two decades that cross-disciplinary approaches were introduced into eating and food sensory studies. During the last decade, increased use of physiological methodologies and techniques has been reported by food scientists. Food texture studies have been conducted in combination with the observation of orofacial muscle activities and the analysis of saliva interactions. Very recently, fNMI (functional Nuclear Magnetic Imaging) observation by neuroscientists revealed positive correlations between increased brain activities and the eating and sensory pleasure perception. Eating is no longer seen as a simple

process of food break down, but is recognised as a highly sophisticated process of human responses (physiological, psychological and neurological) to the changing physicochemical properties of the food.

Based on this background, we feel that there is a need for a book that elucidates the multi-disciplinary nature of eating and sensory perception and that reviews the latest progress in related areas, from fundamental studies to industrial applications. This book endeavours to be a multi-disciplinary source of stimulation and reference, and we hope it will encourage further researches in these areas. The book is divided into five sections: 1 Oral anatomy and physiology; 2 Food oral management; 3 Oral processing and sensory perception; 4 Principles and practices of instrumental characterisation for eating and sensory perception studies; and 5 Applications and new product development.

The first section covers the oral cavity, where Luciano Pereira describes the anatomy and function of the different parts of the oral cavity; oral receptors, where Lina Engelen reviews the oral tactile and chemosensory receptors; and saliva, where Guy Carpenter discusses the origins and composition of saliva as well as its role in the oral processing of food. In Section 2 Andries van der Bilt starts by discussing the strategies of food oral management, from ingestion to swallow; followed by a chapter on the oral break down and mastication of solid foods and the determining physical principles (Carolyn Ross and Clifford Hoyer Jr.). Anwesha Sarkar and Harjinder Singh introduce food emulsions and their behaviour in the mouth. This chapter explains the possible mechanisms of oral destabilisation of food emulsions and their implications on sensation. The section ends with a review by Jianshe Chen on the mechanisms of food bolus formation and the critical criteria in triggering a swallowing action.

The third section of the book covers the interactions between oral processing and sensory perception, regarding texture by Lina Engelen and Rene de Wijk, and flavour by Sara Adams and Andrew Taylor, followed by an account of sensory integration and psychophysics by Charles Spence.

Section 4 begins with two chapters by Jason Stokes on 'oral' rheology and 'oral' tribology, in which he discusses the underlying physical principles of food oral break down and food oral movement and their roles in sensory perception. This is followed by a chapter on the EMG (electromyography) technique (by Yadira Gonzalez and Jianshe Chen), covering the theories and practices of the technique and its application to eating studies. Micha Peleg and Maria Corradini conclude Section 4 with a chapter on food–body interactions, where, by treating the human mouth as a soft machine, soft machine mechanics are discussed in relation to instrumental characterisation of textural properties of a food.

The final section is dedicated to possible applications of recent research findings for new product developments. Paula Varela and Susana Fiszman focus mainly on crispy and crunchy foods and the principles and practices applied in industry in designing and providing such products. Adam Burbidge finishes off the book by reviewing the biomechanics of oral stress and strain, which (micro-)structures elicit these effects, and considers potential routes for creating these structures in a food context.

Integrated studies of eating and sensory perception have been adopted only fairly recently and this book is probably the first of its kind. We anticipate that this book will be of interest to scientists, technologists and engineers in food-related areas, as well as to those from other disciplines such as oral physiology, oral biology, dentistry and sensory science. This book could also be used as a useful reference for undergraduate and postgraduate students studying in above disciplines and for R&D researchers in food manufacturing and food service industries.

We would like to take this opportunity to thank all the contributors; their expert knowledge, enthusiasm and hard work have enabled us to put a book together of high scientific quality; the editorial staff at Wiley-Blackwell for their support and advices; and our families and friends for bearing with us through the long nights and weekend hours.

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Part One

Oral Anatomy and Physiology

1 Oral Cavity

Luciano José Pereira

1.1 INTRODUCTION

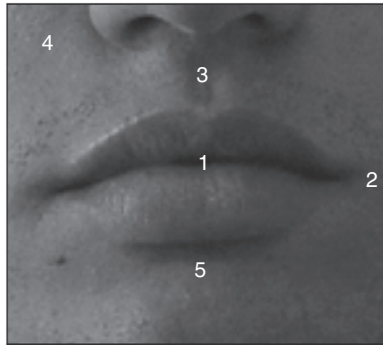
The oral cavity is the first part of the digestive tract. However, the mouth is not only responsible for digestive functions. It also plays a role in breathing, behavioural and social activities (talking, smiling, yawning, sucking) and taste perception. The oral cavity consists of two parts: the vestibule, which is limited externally by the lips and cheeks and internally by the gums and teeth; and the oral cavity itself (1.1), which is limited laterally and ventrally by the alveolar process and teeth and dorsally communicates with the pharynx through the *isthmus faucium* (Gray, 2000).

Mastication is the most important function of the mouth. Teeth, muscles of mastication and salivary glands all work together to shred and break down food for swallowing. The teeth are the hardest tissues in the jaw and are involved in different activities, such as food ingestion and pronunciation of words, and also play an important role in facial aesthetics (Honda *et al.*, 2008; Koussoulakou *et al.*, 2009). The muscles of mastication promote the force needed to elevate the jaw so that food can be shredded between the teeth as the upper and lower arches come into contact (Fontijn-Tekamp *et al.*, 2000). Simultaneously, saliva is produced by major and minor salivary glands. The water in saliva moistens food particles and salivary mucins bind masticated food into a coherent, moist bolus that can be easily swallowed (Pedersen *et al.*, 2002).

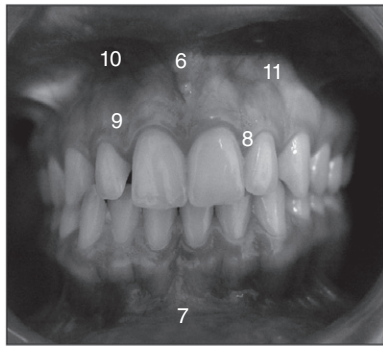
This chapter reviews the main anatomical and physiological aspects of the oral cavity – teeth, tongue, salivary glands and major orofacial muscles. The review focuses on the physiological behaviour of the mouth and fundamental knowledge of oral operations covered in four main sections: the oral cavity (including teeth and periodontal tissue); saliva (saliva glands, saliva secretion, composition, physical and chemical properties); orofacial muscles (location, function, activity) and tongue (tongue muscles, function).

1.2 THE ORAL CAVITY

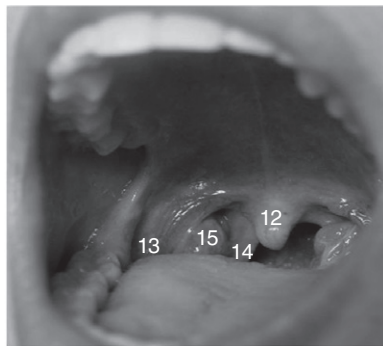
The oral cavity is delimited anteriorly by the upper and lower lips (vermilion surface, mucosal lip, labial mucosa), laterally by the cheeks, superiorly by the hard palate and



- 1 Lips
- 2 Mouth angle
- 3 Filtrum
- 4 Nasolabial sulcus
- 5 Labiamental sulcus



- 6 Upper lip frenulum
- 7 Inferior lip frenulum
- 8 Interdental papillae
- 9 Gum
- 10 Alveolar mucosa
- 11 Vestibulum



- 12 Uvula
- 13 Palatoglossal arch
- 14 Palatopharyngeal arch
- 15 Palatine tonsil

Figure 1.1 The oral cavity.

inferiorly by the tongue and muscles attached to the internal side of the mandible, including the geniohyoid, mylohyoid and digastric muscles. The upper and lower dentition, salivary glands, mucosal glands, tongue and the mucosal tissue covering the hard palate are found in this cavity (German and Palmer, 2006) (Figure 1.1).

The oral cavity is continuous with the pharyngeal cavity. The region where the pharynx connects to the oral cavity is called the oropharynx, and it embraces the base of the tongue, vallecula, soft palate, uvula, lateral pharyngeal walls (including the palatine tonsils and tonsillar pillars) and the posterior pharyngeal wall extending from the plane of the soft

palate/hard palate junction to the level of the pharyngoepiglottic folds at the hyoid bone. The base of the tongue is the part posterior to the circumvallate papillae (Yousem and Chalian, 1998).

The mucous membrane that covers the mouth connects to the integument at the free margin of the lips and with the mucous covering the pharynx. It has a rose-pink colour and it becomes thicker on hard parts limiting the cavity. The mucous membrane is covered by stratified squamous epithelium (Gray, 2000).

The bones adjacent to the oral cavity are the maxilla and mandible. These bones support the dentition and form the hard palate, which is made up of the palatine process of the maxilla and the maxillary process of the palatine bones. The final portion of the oral cavity is formed by muscle, with the hyoid bone and cartilages of the larynx functioning as the pharyngeal arch structures (German and Palmer, 2006).

The dentition is placed in the maxilla and mandible and consists of 32 teeth. Children are born edentulous; the first deciduous (primary) teeth erupt approximately six months after birth. There are five types of deciduous teeth: medial incisor, lateral incisor, canine, first molar and second molar. These teeth are replaced by permanent teeth. However, the permanent dentition is composed of two additional premolars and a third molar. The permanent dentition is usually complete (except for the third molar) at 12 years of age. The third molar erupts at around 16 to 20 years of age and frequently fails to erupt at all (German and Palmer, 2006). Some individuals do not even present those teeth (agenesia).

The main component of a tooth is dentine, which is calcified tissue produced by odontoblasts (Koussoulakou *et al.*, 2009). The dentine surrounds the pulp, which is rich in fibroblast-like cells, blood vessels and nerves. The dentine that forms the tooth crown (the visible part of the tooth in the oral cavity) is covered by a layer of enamel, which is produced by ameloblasts. The enamel is the hardest tissue in the human body and is collagen free. Its main proteins are amelogenin (90%), ameloblastin, enamelin and tuftelin. The teeth are firmly attached to the jaw by their roots, which support the teeth within an alveolar socket by means of the periodontal ligament. The periosteum is connected to the fibrous structure of the gums (Gray, 2000).

The teeth are important to the masticatory system, as they break down food particles during occlusal contact (Pereira *et al.*, 2006). A significant reduction in masticatory function occurs following the loss of post-canine teeth. Moreover, individuals with natural dentition present better masticatory function than those who wear removable dentures or have an implant-supported prosthesis (van der Bilt, 1994; Wilding, 1993; Julien *et al.*, 1996; Fontijn-Tekamp *et al.*, 2000; Hatch *et al.*, 2001; van Kampen *et al.*, 2004). A linear relationship has been found between masticatory performance and the number of occluding teeth (van der Bilt *et al.*, 1993). However, individuals who have lost posterior teeth do not necessarily chew longer before swallowing than individuals with all teeth. This indicates that, on average, people with a bad masticatory performance swallow larger food particles (Fontijn-Tekamp *et al.*, 2004).

Tooth loss is related not only to a reduced occlusal area, but also to the disappearance of the periodontal ligament. Mechanoreceptors located in the periodontal ligament obtain detailed information on the spatial relationship and load modulation in the process of food fragmentation (Johanson *et al.*, 2006). Thus, chronic periodontal disease can cause the destruction of the support tissue, with consequent loss of periodontal mechanoreceptors, resulting in tooth mobility and masticatory impairment (Alkan *et al.*, 2006). The subjective perception of the impact of oral health on mastication diminished after periodontal treatment (Pereira *et al.*, 2011).

1.3 SALIVARY GLANDS AND SALIVA SECRETION

The major salivary glands are characterized by three pairs of organs: parotid, submandibular (Figure 1.2) and sublingual glands that work simultaneously to produce saliva for the oral cavity (Denny *et al.* 1997). The major salivary glands secrete more than 90% of the total volume of saliva and the remaining amount is secreted by the minor glands. These glands are located all over the mouth except the gums and anterior portion of the hard palate (Tenovuo, 1997). Salivary glands are made up of acinar and ductal cells. The formation of saliva inside the salivary glands occurs in a similar manner to the action of the tubular filtration in the kidneys. A plasma-like filtrate is formed by the acinar cells. Initially, this fluid is isotonic with respect to blood plasma. During its way through the gland ducts the filtrate becomes hypotonic due to resorption and secretion of ions and other components. (Turner *et al.*, 2002; Dodds *et al.*, 2005). Secretion is controlled by the autonomic nervous system. Parasympathetic stimulation induces the output of a large volume of saliva with a low protein concentration, whereas sympathetic stimulation has the opposite effect, causing the release of a relatively small volume of saliva, with a high protein concentration (Anderson *et al.*, 1984). Even though both parasympathetic and sympathetic stimulation can evoke salivary flow, stress situations can cause dry mouth symptoms due to vasoconstriction.

The parotid gland (Figure 1.2) is located in the retromandibular fossa anterior to the ear and sternocleidomastoid muscle. Parts of the superficial lobe cover the ramus of the mandible and the posterior part of the masseter muscle (Bialek *et al.*, 2006). The acinar cells of the parotid gland produce a largely serous secretion and synthesise most of the α -amylase (Llena-Puy, 2006).

The submandibular gland (Figure 1.2) is located in the posterior portion of the submandibular triangle. The submandibular triangle is limited by the anterior and posterior bellies of the digastric muscle as well as the body of the mandible. (Bialek *et al.*, 2006).

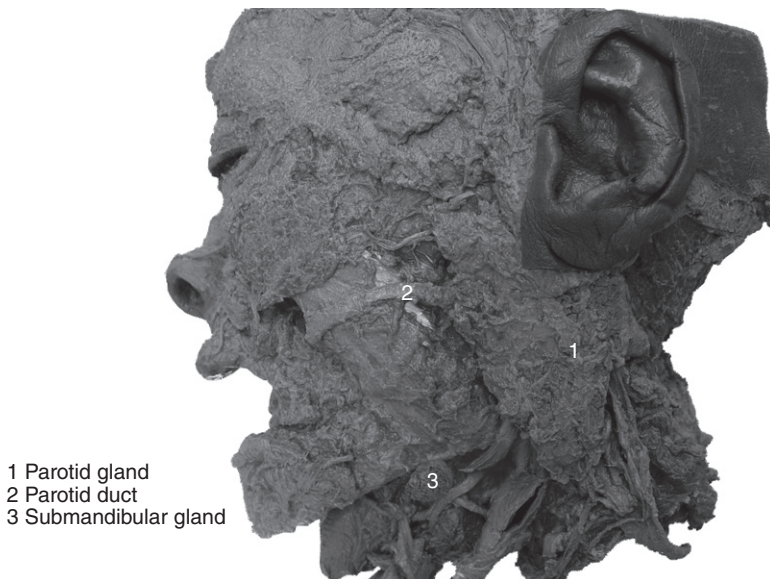


Figure 1.2 Parotid and submandibular salivary glands.

The sublingual gland lies between the muscles of the oral cavity floor – geniohyoid muscle, hyoglossal muscle (medially), mylohyoid muscle and intrinsic muscles of the tongue. Its lateral side is adjacent to the mandible (Bialek *et al.*, 2006). Mucins are glycosylated proteins, mainly produced by the submandibular and sublingual glands, whereas proline-rich and histatin-rich proteins are produced by the parotid and submandibular glands. The minor salivary glands are basically mucus (Llena-Puy, 2006) and they play an important role in lubricating the mucosa, thereby accounting for a large fraction of the total secretion of salivary proteins. The minor glands, which are distributed throughout the oral mucosa (labial, buccal, lingual, palatal mucosa), are mixed glands largely comprising mucous acinar cells (Pedersen *et al.*, 2002).

During non-stimulated salivary flow, about 20% of the volume is secreted by the parotid glands; about 65 to 70% by the submandibular glands, around 7 to 8% by the sublingual glands and less than 10% by the minor salivary glands. When salivary flow is stimulated, the parotids contribute more than 50% of total salivary secretion (Edgar *et al.*, 1992).

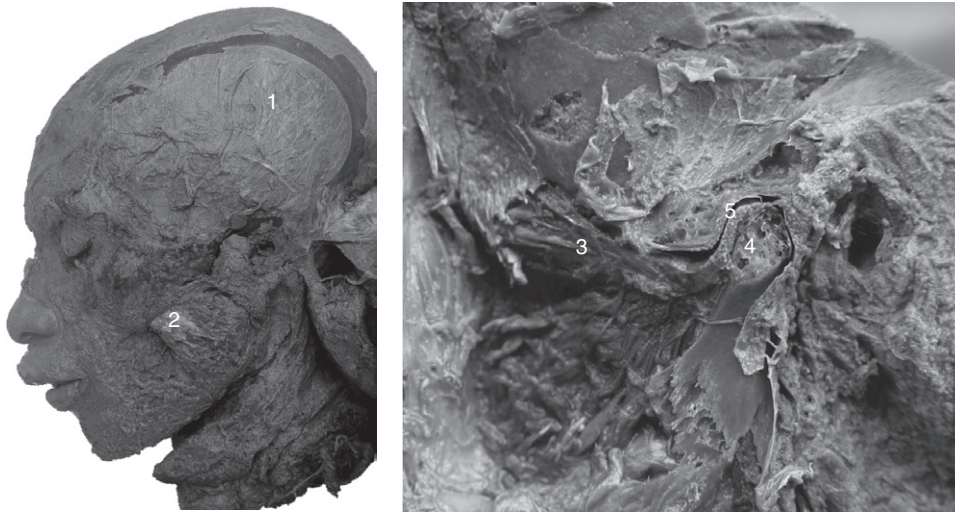
Saliva is basically composed of water. However, it also contains several diluted electrolytes (sodium, potassium, calcium, chloride, magnesium, bicarbonate, phosphate); proteins (albumin) and enzymes; immunoglobulins and mucosal glycoproteins, among other peptides. There is also glucose, urea and ammonia (Edgar, 1992; Humphrey and Williamson, 2001).

Saliva is involved in taste perception, as its high water content provides the capacity to dissolve substances and allows the gustatory buds to perceive different flavours (de Almeida *et al.*, 2008). Additionally, saliva mucins lubricate the food bolus and protect oral tissues from irritating agents (Nagler *et al.*, 2004). The water in the saliva moistens food particles, allowing salivary amylase to access available starch. The salivary mucins bind masticated food into a coherent, moist bolus that can easily be swallowed (Pedersen *et al.*, 2002). The dilution effect seems to be the most important factor related to digestive properties, since the act of adding fluids to the food significantly reduces the number of chewing cycles and total muscle effort. The type of fluid (water, artificial saliva containing mucins or a solution of α -amylase) has been found to have no significant effect on the chewing process (van der Bilt *et al.*, 2007) and salivary flow does not seem to have a significant influence on masticatory performance (de Matos *et al.*, 2010). In addition to diluting substances, saliva provides the mechanical removal of residues, non-adherent bacteria and food debris (Almeida *et al.*, 2008).

The most known enzyme of saliva is α -amylase, which breaks carbohydrates down to maltoses by cleaving the α -1-4 glycosidic bindings. Salivary α -amylase is considered to be of small significance in digestion because of its rapid inactivation in stomach (Pedersen *et al.*, 2002). Salivary α -amylase is secreted mainly from the serous acinar cells of the parotid and submandibular gland. An additional salivary digestive enzyme is lingual lipase, which is secreted from acinar cells of the serous von Ebner's glands located on the posterior region of the tongue and beneath the circumvallate papillae. Lingual lipase is, however, considered to be of limited significance (Pedersen *et al.*, 2002).

1.4 OROFACIAL MUSCLES

The anterior limit of the oral cavity is formed by the orbicularis oris muscle, which surrounds the opening of the mouth. The labial muscles also control the lips and therefore the movements of the mouth: levator labii superioris, depressor anguli oris and risorius. The



- 1 M. temporalis
- 2 M. masseter
- 3 M. external pterygoid
- 4 Condyle
- 5 Articular disc

Figure 1.3 Muscles of mastication.

buccinator is the cheek muscle. These are superficial facial muscles and receive motor supply from branches of the facial nerve (VII) (German and Palmer, 2006).

Although they do not form the boundaries of the oral cavity or pharynx, the muscles of mastication are critical to moving the jaws and therefore oral function. The muscles of mastication are the masseter, temporalis, internal pterygoid (raisers of the mandible) and external pterygoid muscle (mandible protruder) (Figure 1.3). These muscles act in a group more than individually. They move the mandible in different directions, with the temporo-mandibular joint acting as a fulcrum. They are innervated by the motor root of the trigeminal nerve (Madeira, 2003).

The masseter consists of two portions, superficial and deep. The superficial portion, which is larger, arises from a thick, tendinous aponeurosis of the zygomatic process of the maxilla and from the anterior two thirds of the lower border of the zygomatic arch (zygomatic-temporal suture); its fibres pass downward and backward (Gray, 2000). The smaller deep portion arises from the posterior third of the lower border and from the whole of the medial surface of the zygomatic arch; its fibres are more vertical and pass downward and forward. Both portions are inserted into the angle and lower half of the lateral surface of the ramus of the mandible (Gray, 2000). The masseter is the most powerful jaw elevator muscle.

The temporal muscle arises from the whole of the temporal fossa and from the deep surface of the temporal fascia. Its fibres converge as they descend and end in a tendon, which passes into the zygomatic arch and is inserted into the medial surface, apex and

anterior border of the coronoid process as well as the anterior border of the ramus of the mandible (Gray, 2000). It is divided into three portions based on fibre position: anterior, mid and posterior. The fibres are more vertical in the anterior portion and gradually become horizontal in the posterior region. Thus, the fibres of the anterior portion are more active during mouth closing and the posterior fibres are basically jaw retruders.

The external pterygoid muscle extends almost horizontally between the infratemporal fossa and the condyle of the mandible. It arises from two heads: an upper head from the lower part of the lateral surface of the great wing of the sphenoid and from the infratemporal crest; and a lower head from the lateral surface of the lateral pterygoid plate. Its fibres pass horizontally backward and laterally and are inserted into a depression in front of the neck of the condyle of the mandible as well as into the front margin of the articular disk of the temporomandibular articulation (Gray, 2000). The simultaneous contraction of both right and left external pterygoid muscles causes the jaw to move forward. When associated to contraction of the suprahyoid muscles (especially the digastric muscle), the mandible rotates and the mouth opens. If only one external pterygoid acts at a time, it moves the jaw to the opposite side (lateral movement) (Madeira, 2003).

The internal pterygoid muscle arises from the medial surface of the lateral pterygoid plate and the grooved surface of the pyramidal process of the palatine bone; it has a second slip of origin from the lateral surfaces of the pyramidal process of the palatine and tuberosity of the maxilla. Its fibres pass downward, laterally and backward and are inserted by a strong tendinous lamina into the lower and back part of the medial surface of the ramus and angle of the mandible at the height of the mandibular foramen (Gray, 2000).

The supra-hyoid muscles comprise the muscles of the oral floor. These are sheets of parallel fibrous tissue running from the hyoid bone to the mandible and include the digastric (V3 and VII), mylohyoid (V3) and geniohyoid (XII and C1) muscles (Figure 1.4). The digastric muscle is believed to be the principal muscle of jaw opening, whereas the geniohyoid is the most important muscle for elevation of the hyoid bone. The supra-hyoid muscles are in a group designated jaw retruders and mouth-opening muscles (Gray, 2000).

Masticatory muscle activation and coordination determine the direction of jaw movement and control occlusal force (Herring, 2007). The thickness of the muscles of mastication affects facial dimensions and bite force (Pereira *et al.*, 2007; Castelo *et al.*, 2010). The functioning of the jaw muscles is highly dependent on the physiological properties of their motor units. These properties (force output, fatigability and contraction speed) vary considerably (Van Eijden and Turkawski, 2001). The jaw-closing muscles seem more adapted to performing slow, tonic movements and producing a smooth, gradable force. In contrast, the jaw-opening muscles seem more adapted to producing faster, phasic movements (Korfage *et al.*, 2005).

The soft palate is the upper limit of the oropharynx and consists of several muscles joining in an aponeurosis: tensor veli palatini, levator veli palatini, palatopharyngeus, uvulus and palatoglossus. The principal elevator of the soft palate is the levator veli palatini, but all of these muscles play an important role in opening or closing the airway during swallowing (German and Palmer, 2006).

1.5 THE TONGUE

The tongue plays a major role in food ingestion. When the tongue moves during the mastication process the food progresses distally through the oral cavity, from the anterior region

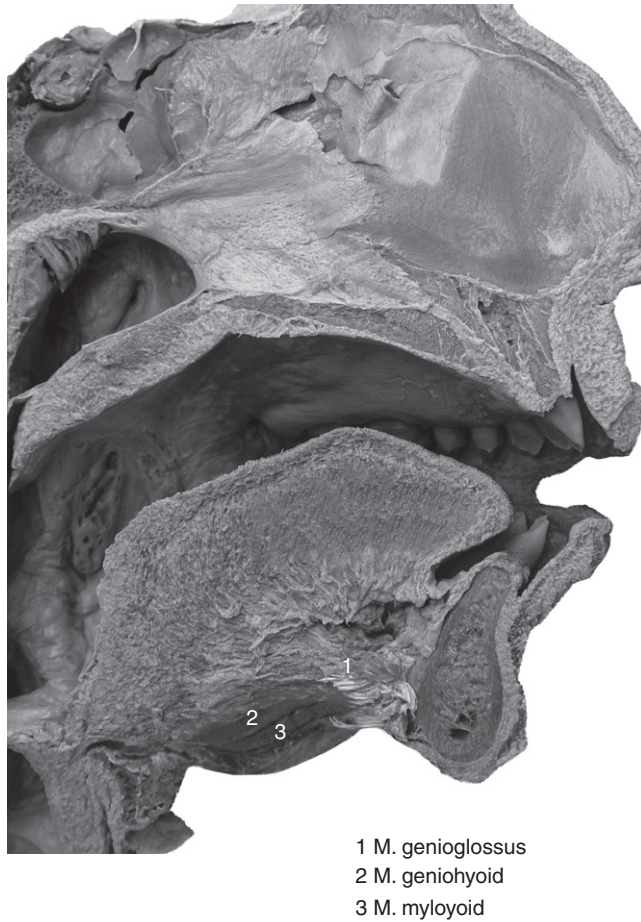


Figure 1.4 The supra-hyoid muscles.

to the pharynx, for bolus formation and swallowing. Chemoreceptors and mechanoreceptors on the tongue surface sense the nature and mechanical properties of food (Hiimae and Palmer, 2003). In addition, tongue position is also important for breathing and talking.

The dorsum of the tongue is convex and marked by a median sulcus, which divides it into two symmetrical halves. This sulcus ends in a depression called *foramen cecum*, from which a shallow groove denominated the *sulcus terminalis* runs laterally and forward on both sides of the tongue. The anterior surface of the tongue is covered with papillae; the posterior region is smoother and contains numerous muciparous glands and lymph follicles (lingual tonsil) (Gray, 2000). There are different kinds of papillae. Circumvallate papillae are located on the dorsum of the tongue right in front of the foramen cecum and sulcus terminalis, forming a row on both sides; these papillae run backward and medially and meet at the mid line, forming an inverted V shape. Foliate papillae are clustered into two groups positioned on each side of the tongue just in front of the 'V' of the vallate papillae; these papillae are involved in taste sensation and have taste buds on their surfaces. Fungiform papillae are found both at the sides and apex, but are also scattered irregularly and sparingly



Figure 1.5 The tongue: taste areas and papillae disposition.

over the dorsum; these papillae are differentiated by their larger size, rounded eminences and deep red colour. Filiform papillae are very small, hair-like papillae that cover the anterior two-thirds of the tongue (Figure 1.5). Additionally, taste buds are placed all over the mucous membrane of the mouth and tongue at irregular intervals and are the end organs of the gustatory sense (Gray, 2000).

Taste is an important part of feeding behaviour. The gustatory cells detect nutritionally important and harmful components in food and triggers innate behaviour leading to either the acceptance or rejection of potential food sources (Yarmolinsky *et al.*, 2009). Taste receptor cells are located on the surface of the tongue and palate. These receptors are organised into taste buds, which are round structures with 50 to 100 cells (Lindemann, 2001). Taste signals from the fungiform taste buds and palate are transmitted to neurons in the geniculate ganglion via the chorda tympani and greater superficial petrosal nerve, respectively, whereas the circumvallate and foliate papillae are innervated primarily by the glossopharyngeal nerve, composed of fibres initiating from the petrosal ganglion. Taste information from sensory ganglia converges on the rostral portion of the nucleus of the solitary tract in the brainstem, from where it is sent to the ventral posteromedial nucleus

of the thalamus. From the thalamus, projections connect to the primary gustatory cortex in the insula. Taste perception is initiated by the physical interaction of tastant molecules with specific receptor proteins present on the surface of taste receptor cells (Yarmolinsky *et al.*, 2009).

Anatomically, the tongue is formed by the extrinsic (muscles with origin outside the tongue body) and intrinsic muscles (muscles with origin and insertion in the tongue body). These muscles act together in most tongue movements, which are not restricted to the protrusion–retrusion axis and involve intricate three-dimensional changes in tongue shape (Sokoloff, 2004). The tongue is formed by four extrinsic muscles (genioglossus (XII), hyoglossus (XII), styloglossus (XII) and palatoglossus (X or XI)) and four intrinsic muscles (vertical, transverse, superior longitudinal and inferior longitudinal). The intrinsic muscles are all supplied by the hypoglossal nerve (XII), have no bone attachments and perform the more accurate movements (Sawczukl and Mosier, 2001). The genioglossus is an extrinsic muscle in that it originates from the mandible.

The neural supply to the tongue consists of three parts: the motor supply; a general sensory element, including the lingual nerve (V3) to the anterior two thirds and branches of the glossopharyngeal nerve (IX) to the posterior one third; and a small area near the base supplied by the internal laryngeal nerve (X). The sensation of taste is supplied by the chorda tympani (a branch of the facial nerve (VII)) to the anterior portion and by the glossopharyngeal (IX) and internal laryngeal (X) nerves to the posterior one third (German and Palmer, 2006).

The function of each muscle of the tongue is determined by the direction of the fibres. The posterior fibres of the genioglossi muscle move the root of the tongue forward and protrude the apex from the mouth. The anterior fibres move the tongue back into the mouth. The two muscles acting together draw the tongue downward so as to make its upper surface concave, forming a channel along which fluids pass toward the pharynx. The hyoglossi depress the tongue and move down its sides. The styloglossi draw the tongue upward and backward. The glossopalatini move the root of the tongue upward (Gray, 2000). The intrinsic muscles are particularly involved in altering the shape of the tongue, whereby it becomes shortened, narrowed or curved in different directions; (Gray, 2000).

1.6 CONCLUDING REMARKS

Mastication is one of the most important functions in the maintenance of general health. It initiates the digestive process, which is responsible for providing the nutrients necessary for cell activities. Prevention and treatment against common pathologies associated with the masticatory system (e.g. tooth deficiency, periodontal disease, temporomandibular dysfunction and dysfunction of the masticatory muscles, salivary glands) are important in order to improve one's quality of life.

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2 Oral Receptors

Lina Engelen

2.1 INTRODUCTION TO ORAL RECEPTORS

2.1.1 Babies sense the world around them through the mouth

Young children and babies are known to put everything they can get hold of into their mouths. There is a good reason for this. At a young age, humans have not yet developed the sensitivity of their fingertips, and while at birth the eyes can only focus on objects at about 30cm, the mouth is already a well developed sensor. Babies have a strong urge to explore and learn about the world around them, and one of the ways they can experience how an object feels is to put it in the mouth and manipulate it with the lips and tongue. In this way the very young child learns what soft, hard, rough, cold and warm is and feels like. The mouth can do this long before the fingers are able to pick up on these sometimes very subtle differences. Most objects also have a flavour, which is interesting for the small baby to experience when their whole repertoire of food experiences usually is restricted to milk, with a hint of what mum had the day before (Beauchamp and Mennella, 2009).

The importance of the mouth as a receiver for tactile and chemical stimuli remains into adulthood. The oral area is one of the most sensitive parts of the body. The lips and tip of the tongue are even more sensitive than the finger tips (Bukowska *et al.*, 2010). Considering the sensitivity and the number of fine muscles in the oral region, as in the finger tips, it is not strange that many of our tokens of affection are directed to and from these body parts. But perhaps the most important role of the mouth is to ingest food. We all enjoy food, not only for its stomach filling properties, but also because of the pleasure it brings us to experience the various tastes, textures and temperatures of food and drink.

In this chapter we will discuss the basic functions and mechanisms of the tactile, gustatory and olfactory receptors present in the mouth and in what way they influence how we process and perceive food. For more detailed information, please refer to the suggested reviews/literature mentioned throughout the text.

2.1.2 Receptors

Receptors throughout the body provide the central nervous system with vital information about the body and its environment. Thus the posture of the body, its supply with nutrients

and oxygen, the state of the cardiovascular and digestive systems, as well as the body temperature and ion concentrations are constantly monitored by sets of sensory cells. Information about objects in the environment, their shape, colour, chemical composition, their distance and movement are collected and conveyed to the central nervous system. This steady and complex flow of coded information is then integrated into a perception and used to generate suitable actions. Each sensory cell detects specific stimuli using highly specialised structures that operate as receptors for adequate stimuli. The receptor must be selective as well as sensitive. The oral receptors are the first step in perceiving food and manipulating food safely and effectively in the mouth.

Humans have four classes of receptors, each of which is sensitive primarily to one modality of physical energy – mechanical, thermal, chemical and electromagnetic. In the mouth all types, except the photoreceptors sensitive to electromagnetic energy, are present. The mechanoreceptors mediate sensations of touch and proprioception; the thermoreceptors sense the temperature of the body and objects that we come in contact with; nociceptors signal sensations of pain; and chemical receptors respond to taste and smell. All these types of receptors contribute to the total sensation and perception of food that we ingest.

2.1.3 Innervation and transduction

The oral region is innervated by three cranial nerves that carry sensory information from the oral region to the brain: trigeminal (V), facial (VII) and glossopharyngeal (IX) Table 2.1.

The trigeminal nerve consists, as the name implies, of three branches that together innervate most parts of the orofacial region. The trigeminal nerve is responsible for the sensation of tactile, proprioceptive, temperature and painful stimuli. The chorda tympani branch of the facial nerve is of greatest importance for sensations of taste as this branch innervates the taste buds of the anterior two thirds of the tongue. The glossopharyngeal nerve (IX) innervates the taste buds of the posterior third of the tongue. The signals evoked by receptors innervated by these cranial nerves are conducted to the cortex in slightly different ways.

Tactile, proprioceptive, nociceptive and thermal information from the receptors in the mouth is conveyed to the central nervous system by the trigeminal somatic sensory system (Figure 2.1). The oral receptors initiate action potentials upon stimulation. These receptors are part of the first order neurons of the trigeminal nerve with cell bodies in the trigeminal ganglia. The trigeminal nerve enters the brainstem at the level of the pons to terminate on second order neurons in the trigeminal brainstem complex. This complex has two major components: the principal nucleus (responsible for processing mechanosensory stimuli) and the spinal nucleus (responsible for processing thermal and painful stimuli). The second-order neurons of the trigeminal brainstem nuclei give off axons that cross the midline and ascend to third order neurons in the ventral posterior medial (VPM) nucleus of the thalamus by way of the trigeminal lemniscus. The axons arising from neurons in the VP complex of the thalamus project mainly to cortical neurons located in the primary somatosensory cortex (SI). Somatic sensory information is distributed from the SI to 'higher-order' cortical fields, such as the adjacent secondary somatosensory cortex, which sends projections to limbic structures, such as the amygdala and hippocampus. On all levels neurons also receive parallel information.

The chorda tympani (part of the intermediate branch of the facial nerve) enters the brain stem at the level of the pontomedullary junction, while the glossopharyngeal nerve enters

Table 2.1 Summary of receptor types and channels for the sensory modalities taste, tactile and olfaction.

Sense		Nerve	Receptor structure /afferent	Channel
Taste	Sour	Chorda tympani (VII) Glossopharyngeal (IX)		TRPP3
	Salt			ENaC
	Sweet			T1R3/T1R dimer
	Umami			T1R1/T1R3 dimer
	Bitter			T2Rs
Tactile	Mechanoception	Trigeminal (V)	SAI, SAII, FAI	DEG/ENaC, TRPs, CNG channels, SLP3
	Nociception	Trigeminal (V)	Free nerve-endings	TRP, ASIC, K+ and ion-ligand gated
	Pungency			TRPV1 (capsaicin)
				TRPM8 (menthol)
	Thermoception	Trigeminal (V)	Free nerve-endings	TRPA1 (garlic) TRPV3 (thymol) TRPM8 (cold) TRPV3, TRPV4 (warm) TRPA1 (noxious cold) TRPV1, TRPV2 (noxious heat)
Olfaction		Olfactory nerve (I)	ORNs	G-protein coupled receptors

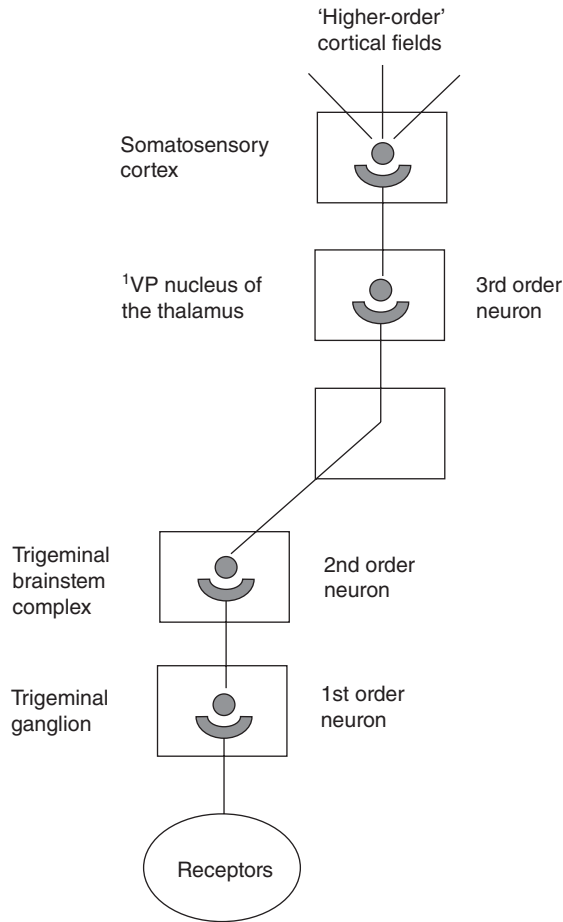
at the level of the rostral medulla (Figure 2.2). Gustatory fibres innervating the taste buds collect in the solitary tract, where after the axons synapse on second-order neurons in the nucleus of the solitary tract (NST) of the medulla. Axons of these neurons project onto the ventral posterior medial nucleus (VPM) of the thalamus. Neurons in the VPM nucleus in turn project into areas of the insular cortex and frontal operculum. There are also connections from the NST to motor systems and parts of the digestive tract, such as the glands that secrete saliva and other glands that secrete digestive fluid. Connections to the pancreas make taste stimulation affect the excretion of insulin.

The representations from each sensory modality (taste, vision, olfaction and touch) are brought together in multimodal regions, such as the orbitofrontal cortex. The signals are integrated into a complete picture, the perception (Rolls and Rolls 2005; Verhagen and Engelen 2006).

2.2 TASTE

The sense of taste, also known as the gustatory system, is primarily involved in feeding, with the main function of identifying food that is rich in nutrients and avoiding toxic substances.

Loss of ability to taste can lead to severely decreased food intake and malnutrition, which in turn can lead to decreased quality of life (Millen 1999). With age, olfactory sensitivity



¹Ventral posterior medial nucleus of thalamus

Figure 2.1 Trigeminal pathway from receptor to higher brain centres.

decreases more rapidly than gustatory sensitivity (Murphy 1986). Even though we often talk about the taste of food, the actual gustatory sensation, including the five basic taste modalities (sweet, sour, salt, bitter and umami), is only a part of the perception we actually are talking about. The rest of the perception comes from the touch (mechanical), trigeminal and olfactory stimuli, together forming the perception of flavour. Flavour reflects the unification of these qualities into a single percept during eating (see also Chapter 10, Section 10.8).

2.2.1 Taste receptors

Taste receptors are located on the apical region of taste cells. The taste cells are clustered in taste buds that contain several types of cells (type I–IV), including supportive cells,

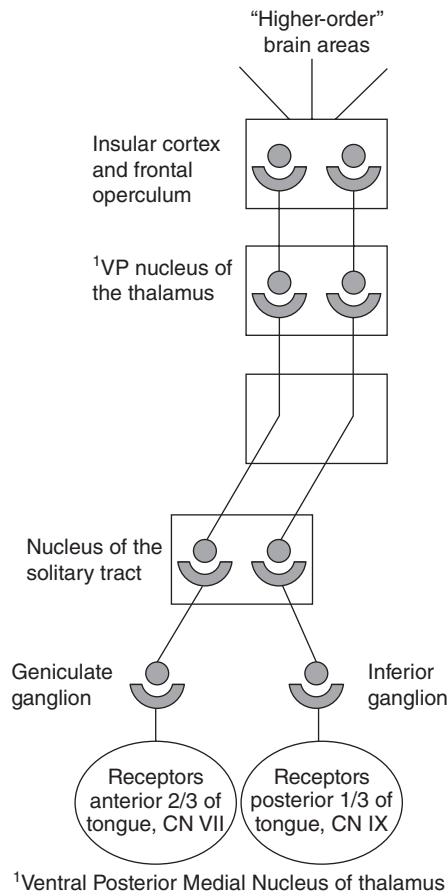


Figure 2.2 Pathway of chorda tympani (CN VII) and glossopharyngeal (CN IX) afferents from receptor to higher brain centres.

progenitor cells and cells that express proteins etc. All taste buds have similar structures and there does not seem to be any variation in sensitivity. Taste buds appear at 7–8 weeks gestation. At this time, however, they are not yet mature and this happens at a later stage. After birth the number of taste buds increases further and they continue to mature. It has been shown that the ability to discriminate between taste stimuli (sweet, bitter and sour, not salt) is innate, but the preference can be modified by post-natal experience (Beauchamp and Mennella, 2009; Cowart *et al.*, 2004). One taste bud can contain up to 100 taste cells representing all five basic taste qualities. Each taste bud has a pore that is in contact with the oral cavity and through which the tastants can reach the taste receptors. The receptors are transmembrane proteins that admit the ions that give rise to the sensations of salty and sour and bind to the molecules that give rise to the sensations of sweet, bitter and umami. A single sensory neuron can be connected to several taste cells in each of several different

taste buds. One or more taste buds reside in taste papillae, which are spread over the tongue, soft palate, upper oesophagus and epiglottis. There are four different types of papillae on the tongue: filiform, fungiform, foliate and circumvallate. Filiform papillae do not contain any taste receptors and are therefore not important for taste perception. They are mechanical and probably involved in the transport of food and perhaps in mechanoreception. Foliate papillae are located on the sides of the tongue, fungiform papillae on the middle and circumvallate are large papillae on the dorsal side of the tongue, on the border with the pharyngeal part of the tongue, and they all contain taste receptors, see Figure 1.5 in Chapter 1.

2.2.2 Taste molecules and modalities

The substances that the gustatory system can detect are water soluble chemicals that are detected during direct contact with the gustatory (taste) receptors in the oral cavity.

Chemical constituents of food interact with receptors on the taste cells. Most taste stimuli are hydrophilic molecules that are soluble in saliva. The gustatory system distinguishes five basic stimulus qualities: salt, sweet, sour, bitter and umami (monosodium glutamate). Recent evidence indicates that fat may represent an additional taste quality (Khan and Besnard, 2009) and the taste system may also be responsive to other classes of compounds (e.g. calcium salts), but less is known about the underlying mechanisms for detecting these nutrients (Bachmanov and Beauchamp, 2007).

Some sensory systems have a single basic type of receptor cell that uses one transduction mechanism (e.g. the auditory system). However, taste transduction involves several different processes, and each basic taste uses one or more of these mechanisms. Taste stimuli may either, pass directly through ion channels (salt and sour), bind to and block ion channels (sour and bitter), bind to and open ion channels (some sweet amino acids), and bind to membrane receptors that activate second messenger systems that, in turn, open ion channels (bitter, sweet, umami). The detection thresholds for substances that evoke these sensations vary greatly.

2.2.2.1 *What substances give rise to the different sensations?*

Sour

The sour taste is brought about by acids. The 'functional' part of acids in the sensation of sourness is the hydrogen ion but, depending on the associated anion, there is considerable variation in the degree of sourness of different acids. The thresholds for citric acid has been reported to be around 0.5 to 1.5 mM (Brosvic and McLaughlin 1989) and others have reported a detection threshold for acids around 0.6 mM on average (Paulus and Reisch 1980). The search for transduction mechanisms of sour-sensitive cells has proved difficult due to the fact that the pH of the stimulus affects many channels and proteins and therefore it is difficult to localise the actions of pH changes (Frings, 2009). However, at present the best potential candidate for a specific proton sensor in sour taste receptors is an ion channel from the TRPP (Transient Receptor Potential Polycystic) family, TRPP3 when coexpressed with PKD1L3 (Huang *et al.* 2006) (Figure 2.3). Much remains to be discovered about the actual transduction machinery for acid stimuli, however. Attention has been focused on a search for transducer proteins activated by extracellular protons, whereas the actual target appears more likely to be an intracellular site (Roper 2007).

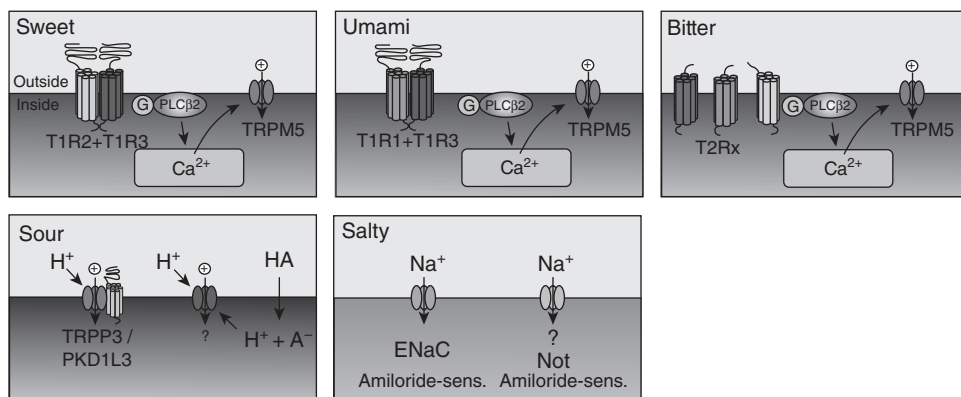


Figure 2.3 Transduction models for the chemosensory membrane of taste cells. The receptor families T1R and T2R mediate sensitivity to sweet, umami and bitter by activating phospholipase β2 (PLCβ2) through a GTP-binding protein (G). The resulting release of Ca²⁺ from intracellular stores opens TRPM5¹ channels which generate a depolarising receptor potential. Sour taste is mediated by a combination of TRPP3² and PKD1L3³ channels. Salt taste may, in part, be mediated by ENaC⁴ channels. (Reproduced by permission of Professor Stephan Frings.)

¹transient receptor potential M5.

²transient receptor potential P3.

³polycystic-kidney-disease-like ion channels.

⁴Na⁺-permeable epithelial sodium.

Salt

The principal stimulus for salty is a common ion, Na⁺. Table salt, NaCl, is the prototypic salty tastant. Na⁺ and Cl⁻ are essential nutrients, vital for maintaining blood volume, blood pressure, regulating body water and, in the case of Cl⁻, maintaining acid/base homeostasis (i.e. Cl⁻ shift). The detection threshold for NaCl is 1 to 15 mM on average in humans depending on the stimulus volume (Brosvic and McLaughlin, 1989; Slotnick *et al.*, 1988). The activation of salt receptors probably involves the activation of sodium receptors, but the strength and taste quality is also modified by the anion present. Hence, salt detection is thought to be dependent on cation ion channels. The exact molecules that mediate salt taste are presently not clearly defined. The best candidate seems to be the epithelial sodium channel ENaC. Na⁺ or K⁺ simply diffuses from the surface of the cell through the channel into salt-sensitive cells, and can hence depolarise the taste cell. Cl⁻ ions are thought to traverse the paracellular route across the taste epithelium together with Na⁺ (Roper, 2007).

Sweet

Most ripe fruit and vegetables taste sweet and contain the most valuable nutrients. Hence perception and the innate preference of sweet taste is likely to have evolved to ensure that we pick and ingest the most nutritious plant parts. Sugar tastes sweet, but there are many other substances that are molecularly very different to sucrose that evoke the same sensation, such as other saccharides, various amino acids, peptides and proteins, as well as artificial sweeteners (Roper 2007). Due to the diversity of the sweet tasting substances it is difficult to give a detection threshold, but the thresholds for sucrose have been reported to be both around 2–5 mM (Zhang *et al.*, 2009) and 14–22 mM (Brosvic and McLaughlin, 1989).

Umami

Umami is the most recent addition to the basic taste modalities. The sensation of umami is conveyed by L-amino acids, including the amino acid glutamate. Umami is most known for being the specific taste in MSG (monosodium glutamate) often used to enhance the flavour of food, but glutamate is also an important nutrient, and it is presumably for this reason that some animals, including humans, have evolved the ability to taste it. Glutamate is found naturally in many foods, including meat, dairy, seafood and tomatoes. For adult humans the detection threshold is about 0.7 mM (Yamaguchi, 1991).

Bitter

Bitter tasting substances are innately disliked because many naturally-occurring toxic compounds taste bitter, hence the commonplace aversion against brussel sprouts in young children. Many plants containing bitter compounds have probably developed this as a deterrent, to protect themselves from 'predators'. Plant-eating organisms have in turn evolved sensory systems to avoid being poisoned (Glendinning, 1994). It is commonly believed that the ability to taste bitterness serves to detect noxious compounds and prevent the animal from consuming harmful foodstuffs. Indeed, bitter taste on the whole has a lower threshold for activation, presumably to prevent consuming even small quantities of toxins. For example, the human detection threshold for caffeine has been reported to be 1 mM and for quinine only 0.05 mM (Paulus and Reisch, 1980). The diversity of bitter compounds is astounding. Amides (e.g. denatonium benzoate) and alkaloids (e.g. caffeine and quinine) are among the most intensely bitter compounds. In addition, many other substances such as certain amino acids, urea, fatty acids, phenols, amines, esters and some salts also taste bitter. Bitterness is however a most acquired taste, as can be seen by the millions of cups of coffee drunk every day all over the world, as well as the dark green vegetables eaten.

Taste receptors for sweet, umami and bitter

There are two families of taste receptors for sweet, umami and bitter taste qualities, T1R and T2R. These are expressed in the chemosensory villi in the apical part of the taste receptor cells. Natural and synthetic sweet stimuli are recognised by a dimer consisting of T1R3 and T1R2 that together form a venus flytrap structure atop taste receptor cells. Umami taste is recognised by the T1R1/T1R3 dimer (Li *et al.*, 2002). Bitter taste is recognised by the T2Rs, a family of about 25 7-transmembrane receptors, although the sensitivities of each receptor to specific bitter compounds, as well as whether there may be other mechanisms for detecting bitter compounds, is still unclear.

Upon activation by sweet, umami or bitter substances, both T1R and T2Rs couple the taste signal to activation of phospholipase C (Zhang *et al.*, 2003) mediated by gustducin (Figure 2.3). This leads to an increase in IP₃ and Ca²⁺, which in turn causes an influx of Na⁺ by activation of the ion channel TRPM5. This depolarisation of the cell can lead the initiation of an action potential.

2.3 MECHANORECEPTION

2.3.1 Tactile stimulation

To control oral motor behaviours such as biting, chewing, speech and oral manipulation, the brain relies on sensory information from oral receptors in the orofacial structures (Lund,

1991; Trulsson and Johansson, 1996b). The mouth is richly provided with these sensitive tactile receptors, the mechanoreceptors. Mechanoreceptors are responsible for relaying information about pressure, vibration, slip and movement taking place in the mouth, and hence play a very important role in both the sensation and perception of food, as well as in the safe manipulation of food.

Mechanoreceptors can be classified on the basis of sensory adaptation. Some receptors respond with a burst of activity when a stimulus is applied, but rapidly adapt and hence decrease their firing rate when the stimulus is maintained. These types of receptors are called fast adapting (FA), or phasic, receptors. They signal changes in the environment, so that we can cease paying attention to situations that remain the same. Most of us are, for example, not continuously conscious of the clothes we are wearing. Conversely, receptors that produce a fairly constant rate of firing when the stimulus is maintained are called slowly adapting (SA), or tonic, receptors and these are well suited for signalling the location of stimulation and fine details. These are important in situations where it is valuable to maintain information about a stimulus, such as when maintaining posture.

The mouth is a very sensitive organ. The oral cavity is one of the body's regions most densely innervated with nerve fibres and receptors (Mountcastle, 1974) and is exquisitely sensitive to chemical and tactile stimulation (Ringel and Ewanowski, 1965; Van Boven and Johnson, 1994). This means that thresholds for somesthetic stimuli are lower and discrimination is better in the oral region than on any other skin areas of the body (Bukowska *et al.*, Essick and Trulsson, 2010). Thresholds for detection of light touch are lowest on the tip of the tongue and hard palate (Henkin and Banks, 1967; Van Boven and Johnson, 1994).

The sensitivity of the skin results from two factors: first density: the number of tactile sensory nerve fibres and receptors present per square centimetre in these areas, and second the area of cortical representation. Areas of the body with a high density of tactile receptors, such as the face, mouth and fingertips are also represented cortically with larger areas of the primary somatosensory cortex. In contrast, low sensitivity to touch in other areas of the body, such as the trunk and back, results from a lower density of sensory fibres and receptor endings, as well as less brain space in the somatosensory cortex (McGlone and Reilly, 2010). Penfield's sensory homunculus (Figure 2.4), the cortical map published in 1950 and spread to be seen in most every book on anatomy and physiology, is quite clever in displaying this relative sensitivity of the different body parts. As can be seen, the lips and tongue have a very large cortical representation in comparison to the legs. One of the reasons why the mouth and face are so highly innervated and well represented in the somatosensory cortex is the importance the face and mouth play in communication (facial expressions and speech, but also affective touch) as well as the importance of food for survival.

2.3.2 Function during eating

In the orofacial region the mechanoreceptors serve two major functions during eating: one is to transmit information about the texture of the food or object that is in the mouth and the other is to provide sensory feedback. This is essential in the control of oral functions, such as the position of the tongue; knowing and manipulating the position of food in the mouth; and guiding the food bolus in the mouth to the right positions for chewing and other manipulation, to prevent biting of the tongue and cheek while guiding the food in the mouth and through to swallowing without choking.

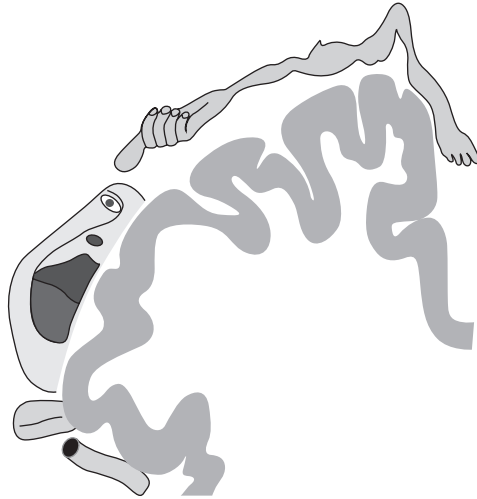


Figure 2.4 Reproduction of Penfield's sensory homunculus depicting the relative cortical representation of different body parts.

2.3.3 Mechanoreceptors in the mouth

The physiology of orofacial mechanoreceptors has been characterised using the technique of microneurography (Trulsson and Essick, 1997). On the hand and arm four types of mechanoreceptors have been found, collectively known as low-threshold mechanoreceptors (LTM), that innervate cutaneous tissue. These comprise of slowly adapting type 1 receptors (SA1) that end in Merkel cells, fast adapting (FA) afferents that end in Meissner corpuscles, SA2 that are thought to terminate in Ruffini corpuscles, and Pacinian (PC) that end in Pacinian corpuscles. Each of these neuron types responds to deformation or motion of the cutaneous surfaces in a different way. However, in the mouth and specifically on the tongue, there is as yet only a little information on the specific morphology of the nerve endings. Nevertheless, functionally, the receptors behave similarly in all areas and those present in the mouth and lip have response properties similar to those of the three classes of mechanoreceptors that innervate the skin of other parts of the human body that have been studied more extensively, such as the hand and arm (Trulsson and Essick, 2010). These are slowly adapting type I and II (SA I and SA II) and fast adapting (FA). No FA2 afferents (Pacinian afferents) have been identified in the face and mouth region (Trulsson and Essick, 2010; Trulsson and Johansson, 2002). Barlow (1987) concludes that sensitivity to high frequency vibration, that is characteristic of the Pacinian-capsule in the finger, was absent in the orofacial region.

Areas of the body that serve to manipulate and explore objects appear to have a large proportion of fast adapting afferents. Conversely, surfaces that deform during function, such as the tongue and lining mucosa, appear to have the largest proportion of SA afferents (Bukowska *et al.*, 2010). The location of the receptors in the tissue suggests what their function is and what type of stimuli they can pick up. SA1 and FA1 are superficial receptors and as such they code spatial and temporal acuity of mechanical stimuli. These receptors are preferentially activated by stimulus surface contact. As the tongue is constantly in motion in relation to surrounding tissues and food inside the mouth during eating, these

two receptors most likely work together in the mouth to create perceptions of food texture (personal comm. Mats Trulsson).

Deep receptors on the other hand have more proprioceptive functions, are probably tightly connected to the muscles of the tongue and could be SAII, Golgi organs or muscle spindles. However, until now the response of specific oral mechanoreceptors to food textures has not yet been assessed (Foegeding *et al.*, 2011). Foegeding and colleagues also discuss the technical difficulties of assessing oral mechanoreceptors' capacity to encode food texture, including difficulties in separating the responses due to the food texture itself and to the force, direction and velocity of movement. It is hence difficult to separate out the functions of the specific receptors during dynamic eating.

What follows is an overview of the oral mechanoreceptor types.

2.3.3.1 SA1 – form and texture

SA1 afferents are sensitive to curvature, edges and points, due to the fact that they are selectively sensitive to components of the local stress-strain field. They are especially sensitive to dynamic rather than static stimuli. Their spatial resolution is about 0.5 mm, although their receptive field diameters are 2–3 mm, and they innervate the skin densely (about 100 per cm² at the fingertip in man (Johnson *et al.*, 2000)). Due to these two principal response properties: responsiveness to features such as edges and curvature, and a high spatial resolution, an acute spatial neural image of a tactile stimulus is transmitted by the SA1 population. In addition, SA1 exhibits a linear response to skin deformation to depths of at least 1500 µm, and is independent of force of application (Vega-Bermudez and Johnson, 1999). The above mentioned remarkable properties of the SA1 afferents make them well suited and responsible for perception of form and texture (Johnson *et al.*, 2000). In the mouth SA1 afferents could sense different textures and shapes of food at different stages of chewing and manipulation.

2.3.3.2 FA1

Historically FA afferents have been known to detect and discriminate low frequency vibration. More recent findings suggest that one of the main functions in the hand is to detect slip between hand and an object and hence provide feedback for grip control (Macefield *et al.*, 1996; Srinivasan *et al.*, 1990). This constant adjustment allows us to manipulate objects with delicacy. FA afferents are highly sensitive to skin motion, but insensitive to static force. FA afferents innervate the skin even more densely (about 150 per cm²) than do the SA1 afferents (Johnson *et al.* 2000). They respond to stimuli over the entire receptive field (3–5 mm), which results in poor resolution of spatial detail, but a robust response to local events such as slip. So what is the function of RA afferents in the mouth? Sensations evoked by microstimulation of orofacial FA1 mechanoreceptors tend to be located superficially in the skin and the sensation has been described as a vibratory sensation or flutter (Trulsson and Essick, 2010). How the responses of these receptors influence how food is sensed in the mouth is not clear and only a little research has been performed in this field.

2.3.3.3 SA2 – shape and position of tongue

Two important roles have been identified for SA2 afferents: the first is perception of an object's direction or force when it produces skin stretch (Olausson *et al.*, 2000). The second

is the perception of hand shape and finger position together with muscle spindles (Collins *et al.*, 2000; Edin and Johansson, 1995). In the mouth, this might translate into shape and position of the tongue. SA2 afferents innervate skin much less densely than SA1 and FA1, but have larger receptive fields with obscure borders. The fact that they are much more sensitive to skin stretch than to indentation, in combination with their deep cutaneous location, leaves SA2 afferents free to signal the object's direction of movement and shape of the tongue, without the confounding effects of indentation produced by an object. In the mouth these receptors are also likely to be responsible for size perception of larger particles and the food bolus when the tongue folds around them, and are hence important for safe manipulation and swallowing of food.

The input from receptors of different oral parts is combined to create a construct of what is sensed in the mouth. They do not always sense the same things and hence can contribute to the final construct in opposing ways. Examples of this were seen in studies in which the size of spheres was estimated orally (Engelen *et al.*, 2002, 2004). While the tongue can fold itself around the sphere and sense the actual size, the palate senses only the smaller part of the sphere that is pressed upon the palate, resulting in conflicting information. This conflicting information led to a tendency to under-estimate the size of the spheres. Covering the palate with an acrylic plate, preventing input to the palatal receptors, removed this bias. In the above study (Engelen *et al.*, 2004) no correlation was found between a subject's spatial resolution of the tongue and their perception of sphere size, which suggests that different receptor afferents are responsible for the two 'sensations'. When topical anaesthesia was applied to the tongue and palate, spatial acuity was reduced, whereas the ability to estimate sphere size was unchanged. One can speculate on the origin of the sensations. Probably superficial receptors of the SA1 type were numbed by the anaesthesia, while more deeply situated receptors, such as SA2, were unaffected. Trulsson and Essick (2010) found that superficial stimulation of SA2 afferents evoked no sensation. The oral perception of sphere size was dependent only on the actual diameter of the sphere and no effects of weight (hence indentation) or material could be observed, which fits with the description of SA2 characteristics.

2.3.4 Proprioceptors

2.3.4.1 Proprioception

Proprioception is the sense of static position and movement of the different body parts. There are two submodalities of proprioception: the sense of stationary position of the limbs and the sense of limb movement. Cutaneous proprioception in the face is especially important for control of lip movement in speech and facial expressions (Gardner *et al.*, 2000). In terms of eating, it is of great importance to know what the position of the tongue, cheeks and lips are while eating, otherwise chances are that we will accidentally bite our tongue etc. Awareness of the position of the tongue is not only important in protecting the soft oral parts, but also for the tongue to pick up food in the correct part of the mouth and bring it to another part. The muscle movements when switching the food bolus from one side of the mouth to the other for chewing or other mastication are very finely tuned. Three types of receptors in muscle and joints transmit proprioceptive information: muscle spindles, situated in the muscles, signal changes in the length of muscles, Golgi tendon organs signal changes in muscle contraction, and receptors located in joint capsules sense flexion or extension of the joint (Gordon and Ghez, 2000). In the oral region proprioceptors are

present in the tendons and muscles of the masseter, temporalis and medial pterygoid muscles. They are also present in the tempomandibular (TM) joint and the surrounding joint tissue.

2.3.4.2 *Muscle spindles*

Muscle spindles are sensitive to stretch and thereby provide information on changes in muscle length. They are found throughout the body of a muscle, in parallel with extrafusal fibres (typical muscle fibres). Muscle spindles consist of a set of specialised muscle fibres known as intrafusal fibres enclosed within a capsule. Intrafusal fibres have contractile proteins at either end, with a central region that is devoid of contractile proteins. The central region is encircled by the sensory endings of the muscle spindle afferent. When opening of the mouth to take a bite of food, the masseter muscle, among others, is stretched. When the muscle lengthens and the muscle spindle is stretched, mechanically-gated ion channels in the cell membrane are opened, causing an influx of Ca^{2+} . This leads to depolarisation and the possible propagation of action potentials in the muscle spindle afferent informing the CNS of the muscle length.

Extrafusal muscle fibres are innervated by efferent neurons known as alpha motor neurons (α -MN), which signal to the muscles how much and how fast they should contract. The intrafusal muscle fibres, on the other hand, are innervated by gamma motor neurons (γ -MN). The role of the gamma MN is to maintain muscle spindle sensitivity, regardless of muscle length. When the extrafusal fibres have been stimulated to contract by alpha MN activation, the gamma MN is simultaneously excited. This is known as alpha-gamma coactivation and results in the fact that the length of the intrafusal fibres are readjusted in order to keep the muscle spindle afferent responsive.

Throughout the body, and specifically in the large muscle groups, one of the most important tasks of muscle spindles is to protect the muscle from over-stretch which could cause damage to the muscles. However, in the mouth, muscle spindles especially play an important role in the modulation of intra-oral transport and food processing. Muscle spindle afferents deep in the tongue encode information about voluntary tongue movements (Trulsson and Johansson, 2002). In conjunction with periodontal receptors, mentioned below, muscle spindles play an important role in the control of jaw movements during normal masticatory function (Lund, 1991). Muscle spindles are involved in regulating the force with which we chew (Hidaka *et al.*, 1999) and monitoring the timing of maximal jaw opening as well as the start of the power stroke during natural chewing. The response properties of muscle spindles are themselves modulated according to the stage in the chewing sequence (Masuda *et al.*, 1997). The ability to feed-forward information from one bite to the next is crucial to send out motor commands that are appropriate for the material properties of food to the jaw muscles before the teeth make contact with the food. In this way, jaw-closing velocity can be kept relatively constant as the teeth come into contact with food at the start of the slow close/power stroke phase. This reduces the effects of changes in external forces acting on the jaw (Abbink *et al.*, 1999).

2.3.4.3 *Golgi tendon organ*

Another type of proprioceptor is the Golgi tendon organ, distributed among the collagen fibrils that form the tendons. Contrary to the muscle spindles, the Golgi tendon organs are

placed in series with muscle fibres. When the muscle contracts, the collagen fibrils are pulled tight, and this activates the Golgi tendon organ receptors. Hence, the Golgi tendon organs are sensitive to muscle contraction and provide information on muscle tension. One would think that muscle stretch would also pull on the tendons and stimulate the Golgi tendon organ afferent. However, during muscle stretch the muscle itself absorbs most of the force and little is carried over to the tendon. The afferents from the Golgi tendon organs synapse onto inhibitory interneurons that in turn synapse onto alpha motor neurons. This negative feedback system regulates muscle tension by decreasing the activation of the muscle during excessive tension and hence has an important protective function. In cases where the Golgi tendon organs fail to inhibit the alpha motor neurons effectively, tendons can be torn off the bone to which they are attached. Hence the basic function of Golgi tendon organs is to protect the muscle, tendons and ligaments from injury. The sense of tension in a muscle can be used for force estimation (Roland and Ladegaard-Pedersen, 1977), which is important in executing efficient chewing.

2.3.4.4 *Mechanoreceptors as proprioceptors*

Mechanoreceptors in the facial skin, lips and buccal mucosa encode contact with environmental objects. However, cutaneous and mucosal afferents also discharge vigorously during contact between the lips, air pressures generated for speech sounds, and to the deformations/strains of the facial skin and oral mucosa associated with voluntary lip and jaw movements. Afferents that monitor tension in collagen fibres might constitute a general proprioceptive system. This system contributes to the maintenance of the body's representation in the central somatosensory system, by registering the mechanical state of the soft tissues. Spontaneously active SA2 afferents in the oral mucosa have been reported to provide such activity (Trulsson and Essick, 2010). Hence, mechanoreceptors of orofacial soft tissues (except for superficial receptors of the tongue) also provide proprioceptive information about orofacial movements (Trulsson and Johansson, 2002).

2.3.5 Periodontal receptors

2.3.5.1 *Function of periodontal receptors*

Teeth are attached to the alveolar bone by the periodontal ligament. This ligament is invaded by nerve fibres terminating in periodontal mechanoreceptors, which respond to loading of the teeth and provide information about the direction in which the forces are applied (Trulsson, 1993). The presence of these receptors make human teeth sensitive to very small forces applied to them (Jacobs and Van Steenberghe, 1994). Signals from periodontal receptors are used in the fine motor control of jaw actions associated with biting, intraoral manipulation and the chewing of food. The periodontal receptors probably especially play a role when eating solid and hard foods.

When food is taken into the mouth, the piece will be split into smaller pieces by the incisors before it is moved to posterior parts of the teeth, see Chapter 4. Sometimes, the incisors are even used as a 'third hand' in manipulative tasks, or as a precision cutting tool. Proper execution of such tasks relies heavily on sensory information (Johansson and Vallbo, 1983). In a 'hold-and-split' task (Trulsson and Gunne, 1998) a peanut was held between the incisors for 3 seconds whereafter it was split. The results showed that subjects with dentures and implants used a much higher and varying holding force than did the normal subjects. In addition, the subjects lacking periodontal receptors lost control of the peanut

and dropped it more often than did the normal subjects. Similar results were shown in subjects with anaesthetised periodontal tissues (Trulsson and Johansson, 1996a), suggesting that periodontal receptors play an important role in the specification of the level, direction and point of attack of forces used to hold and manipulate food between the teeth (Trulsson, 2006).

Periodontal receptors are mostly slowly adapting afferents that encode information on the orientation, magnitude, rate and position of loads applied to the teeth. These afferents are located close to the collagen fibres in the periodontal ligament and are often described as Ruffini-like, (see SA2 mechanoreceptors, above). When a force is applied to the tooth during, for example, biting and chewing, the tooth moves slightly in its socket, which induces stresses and strains in the periodontal ligament. The periodontal receptors respond most strongly when the ligament in which they are located is in tension (Cash and Linden, 1982). A large portion of the human periodontal receptors respond to stimulation of more than one tooth (Johnsen and Trulsson, 2003). The majority of the periodontal receptors are saturating receptors and exhibit curved stimulus–response relationships, where they are most sensitive to forces below approximately 1 N for anterior teeth and approximately 4 N for posterior teeth (Trulsson, 2007). Hence, periodontal afferents of anterior teeth are more sensitive at low tooth loads compared with afferents of posterior teeth. Consequently, the periodontal receptors of the anterior teeth are important in precision tasks including manipulation of food, while the posterior receptors are involved in the feedback regulation of chewing force and so on.

Although there is a central generation of rhythmical chewing movements (Nozaki *et al.*, 1986), these usually don't remain the same throughout the mastication cycle. The central command of mastication is modulated by peripheral inputs (Dellow and Lund, 1971; Lavigne *et al.*, 1987; Ottenhoff *et al.*, 1992) so that the masticatory motor output adapts to the characteristics of the chewed food (Ottenhoff *et al.*, 1992; Wang and Stohler, 1991). Subjects with dental implants, however, often do chew with about the same pattern of muscle activity throughout the entire masticatory sequence (Haraldson, 1983). The lack of adaptation in these individuals is likely attributed to the absence of periodontal receptors. There is some feed-forward modulation in the mouth, where information on the food's resistance gathered during the previous chewing cycle is used to plan and scale the force needed in the subsequent chewing cycle (Ottenhoff *et al.*, 1992). However, the masticatory system is mainly feedback controlled and dependent on reflex activity (Van der Bilt *et al.*, 2006). Food resistance may vary greatly from cycle to cycle and chewing involves application of (often) high bite forces between the hard but brittle enamel surfaces of the teeth. The electrical activity of the chewing muscles will abruptly decrease when the food breaks, thus preventing too fast jaw closing and damage of the teeth. Hence, immediate feedback modulation of jaw movements and bite force, via reflex behaviours based on information from periodontal receptors together with muscle spindles, is necessary to maintain a constant chewing rhythm and to protect the teeth (Turker, 2002).

Signals from periodontal receptors, muscle spindles and Golgi tendon organs report on the forces and length of the masticatory muscles, in addition to the position of the mandible, hence providing information on food characteristics during chewing/eating.

2.3.6 Signal transduction and central processing

Mechanoreceptors directly couple movement to the opening of transduction channels. Oddly enough, this basic and universal sense of touch appears to be one of the most

difficult to study at the level of its transduction mechanism. It is quite clear that mechanical stimuli of various sorts can trigger opening of ion channels and cause depolarisation in practically every cell (Hamill and Martinac, 2001; Kung, 2005). A few mechanisms have been proposed to regulate ion-channel opening in response to a mechanical stimulus. These include ion-channels that are:

- Stretch-activated, which open when forces in the lipid bilayer change, for example due to changes in curvature or tension of the bilayer.
- Tethered, that require links to the cytoskeleton and which open when displacements of these links open the channel (hair cells of the inner ear, see reviews by Grant and Fuchs (Grant and Fuchs, 2007) and Vollrath (Vollrath *et al.*, 2007).
- Indirectly gated, through signalling intermediates. These transduction intermediates might respond to changes in the lipid bilayer or might require tethers (Lumpkin and Caterina, 2007).

Sensory cells which are specialised for the detection of mechanical stimuli (mechanoreceptors) use elaborate protein complexes to transduce mechanical stimuli, and to report a sensory signal to the central nervous system. Extensive research has been performed trying to elucidate the transduction mechanisms of cutaneous mechanosensation (Lumpkin and Caterina, 2007). Although DEG/ENaC, transient receptor potential (TRP) and CNG channels are currently the most investigated as candidate transduction channels, studies suggest that there are other candidates still to be identified. These transduction channels are mostly non-selective cation channels, which are Ca^{2+} – permeable and show little voltage dependence (Frings, 2009). A member of the PHB domain protein family, stomatin-like protein 3 (SLP3), for example, has been shown to be necessary for normal touch sensation in mice (Wetzel *et al.*, 2007). However, up to now, the search for mechanotransduction channels has produced some conflicting results (Chalfie, 2009; Drew *et al.*, 2004; Gottlieb *et al.*, 2008), and the molecular identity of the channels remains hard to pin down.

However, in general the following train of action occurs: when any of these touch-sensitive nerve endings are mechanically deformed, membrane channels are opened and cations enter the cell. This influx of cations creates a change in voltage across the membrane (depolarisation) generating a receptor potential, which triggers action potentials. The action potentials are transmitted along the afferents of sensory nerve cells. Tactile and proprioceptive information from the face is transmitted to the central nervous system via the trigeminal somatic sensory system. Eventually the signal is transmitted to the postcentral gyrus of the primary somatosensory cortex (SI), where touch is actually perceived. All of the tactile information transmitted from the various receptor types in a given body area is combined in the cerebral cortex. It provides a sophisticated analysis of the total pattern of nerve signals so that one can instantly (and consciously) judge the texture, force, location and movement of the stimulus with great precision.

2.4 NOCICEPTION

2.4.1 Nociceptors

The sensation of pain (nociception) serves an important protective function: it warns of injury that should be avoided or treated. Pain is mediated by nerve endings, called nocicep-

tors, tuned to respond to noxious stimuli. Unlike the specialised somatosensory receptors for touch and pressure, the terminals of nociceptive axons do not possess specialised end organ structures and are therefore referred to as free nerve endings. The lack of a protective encapsulation of the nerve endings renders them sensitive to chemicals. In contrast to the low-threshold receptors (LTM) that mediate touch, most nociceptors are high-threshold receptors that require stimuli of high energy to respond, and normally respond to stimuli of sufficient energy to potentially or actually damage tissue.

The normal function of the nociceptor is to be silent except in the presence of imminent danger. In the presence of noxious stimuli that may produce tissue damage, such as intense pressure, extreme temperature or burning chemicals, the nociceptors generate a strong response. This response can be directly to some noxious stimuli and indirectly to others by means of chemicals released from cells in the traumatised tissue (such as bradykinin) (Gardner *et al.*, 2000).

Because peripheral nociceptive axons terminate in free endings it is conventional to categorise nociceptors according to the properties of the axons associated with them. In the skin there are three major classes of nociceptors: the A δ mechanical and thermal nociceptors and the C-polymodal nociceptors, that respond to noxious stimulation of varying origin. A δ fibres have a relatively small diameter, are myelinated, and they propagate signals fairly rapidly (~12 m/s). In contrast, the C-fibres have a smaller diameter and are unmyelinated and propagate signals slowly (<1 m/s) (McGlone and Reilly, 2010). The result of these differences is that A δ fibres transmit the fast and sharp pain, whereas the slow dull pain is transmitted by the C-fibres (Hendry and Hsiao, 2008). C-fibre afferents represent the majority of sensory neurons in the peripheral nervous system. The receptive fields of nociceptive neurons are relatively large, presumably because the detection of pain is more important than the exact location.

As many nociceptors are polymodal neurons, they can be activated by various types of sensory stimuli, often thermal, chemical, and mechanical. Temperatures below and above the cut-off points for thermal perception will elicit sensations of pain, due to the possibility of tissue injury during prolonged contact with very cold or very hot items. This is also the case for chemicals which could potentially cause tissue damage, such as acids, or chemicals that are released as a response to tissue damage, such as histamine and bradykinine.

Pain is usually associated with unpleasantness, but how important is the nociceptive function really? Verpoorten and colleagues (2006) showed that loss of nociceptor neurons in patients with hereditary sensory and autonomic neuropathy type 4, due to a failure of nociceptor survival in the embryo, produces congenital pain hyposensitivity. These unfortunate individuals burn and chew their tongues and lips and, as a result of undetected damage, lose the tips of their fingers and damage joints. Hence, sensation of pain is of paramount importance to recognise and avoid harmful situations. Heightened pain sensitivity can also contribute to healing by helping avoid contact with the damaged body part until repair has occurred.

2.4.2 Nociception in food

One very important task of nociceptors during eating is to make sure we don't bite our tongues, lips or cheeks and burn our mouth. The response to an event like that would be of serious pain, as anyone who has bitten their tongue will recognise, and we would try to avoid that in the future. The mechanical impact caused by biting leading to tissue damage

is a high energy stimulus that initiates high-threshold receptors. Hence, nociceptors are high-threshold receptors that require the stimuli of high energy to respond. However, there seems to be an important role to play in the ingestion and pleasure of food for nociceptors that respond to lower threshold stimuli as well.

During normal eating we perceive a multitude of other stimuli transduced by nociceptors, such as pungency. Some chemicals that in high concentrations could potentially cause damage to the tissues, such as capsaicin (chilli) and eugenol (cloves), produce sensations in the mouth which at low concentrations are considered pleasant, interesting or even necessary for the flavour of some foods. Garlic, chilli and mustard's pungent flavours have made them popular ingredients in cuisines around the world and throughout history. This pungent sensation is often referred to as trigeminal sensation, due to the transduction of these sensations by free nerve ending of afferents from the trigeminal nerve in the oral region. Another example of 'trigeminal sensation' is the carbonation in fizzy drinks. Some individuals show high levels of dislike for foods that are pungent, while others develop preference for their daily use. The sensitivity to these sensations and chemicals varies greatly among people and also within people depending on the site of stimulation within the mouth (Green and Lawless, 1991).

Indeed, low-frequency users of chilli do rate the burn of capsaicin as more intense than frequent users (Prescott and Stevenson, 1995). In many cultures some of these chemicals are used on a daily basis and can, albeit counter intuitively, aid in cooling down, see thermoception, Section 2.5.5. Capsaicin has been shown to trigger the release of endorphins in rats (Bach and Yaksh, 1995), and hence creates a sense of pleasure or wellbeing, or alternatively reduces the sensation of pain. The pungency of capsaicin was probably not developed by plants as a means of pleasure for different animal species, but more as a protection from herbivorous animals (Boiron *et al.*, 1997). Pungency can be thought of as a sensation on the pain continuum, where the resulting sensation depends on the concentration of the stimuli and on the level of sensitivity of the individual.

2.4.3 Nociceptive transduction

The operational components of the nociceptor include a peripheral terminal that innervates target tissue and transduces noxious stimuli, an axon that conducts action potentials from the periphery to the central nervous system, a cell body in trigeminal ganglia, and a central axon that enters the CNS to synapse on nociceptive second order neurons following the trigeminal pathway (Figure 2.1), ultimately leading to a conscious awareness of the noxious stimulus, pain. Transduction of nociceptive sensations is mediated by high-threshold transducer ion channels on the nociceptor, which depolarise the peripheral terminal resulting in the activation of voltage-dependent sodium channels. The sensory specificity of the nociceptor is determined by the expression of ion channels that respond with a high threshold to particular mechanical, thermal and chemical features. The known channels involved in nociceptive transduction include TRP, ASIC and potassium and ligand-gated ion channels (Woolf and Ma, 2007). TRPV1 channels have been shown to be highly expressed on nociceptive A δ - and C- fibres and they are activated by, for example, capsaicin and other chemicals (Caterina and Julius, 2001). TRPV3 and TRPM8 also have nociceptive functions (Bang *et al.*, 2010). Protons can activate members of the ASIC family, generating a perception of pain (McGlone and Reilly, 2010). The channels that transduce pain and temperature are also involved in the perception of pungency. Especially the TRP channels seem to be

sensitive to a collection of pungent chemicals from chilli, peppermint, horseradish, oregano, clove and thyme (Macpherson *et al.*, 2005) and (Xu *et al.*, 2006) as well as to some less pleasant chemicals, such as acrolein, a component of cigarette smoke and vehicle exhaust (Bautista *et al.*, 2006), and to some spider toxins (Siemens *et al.*, 2006). The ion channel TRPA1 is expressed in trigeminal ganglion neurons and is activated by several pungent compounds, including mustard oil (Jordt *et al.*, 2004) and garlic (Macpherson *et al.*, 2005) (Bautista *et al.*, 2005).

The relationship between stimuli and transduction is not simple, and the perception of a single stimulus often requires several transduction mechanisms. Conversely one type of protein can contribute to several senses, such as pungency and heat (Lumpkin and Caterina, 2007). TRPV1 channels are sensitive to temperatures above 43 °C and they also respond to Szechuan pepper and capsaicin (Caterina and Julius, 2001), the key molecule in chilli peppers, which is why chillies and curries are 'hot'. Menthol on the other hand, binds to the TRPM8 receptor channel, which is also sensitive to temperatures in the cool range (~8–28 °C). When menthol binds to the TRPM8 receptor, it has the same effect on the receptor as exposing it to 'cool' temperatures, resulting in the cooling effect of menthol (Peier *et al.* 2002). In addition, Xu *et al.* (2006) found that the response by TRPV3 to carvacrol (oregano) and thymol (thyme) was enhanced by higher temperatures. These examples explain the psychophysical function seen where higher temperatures increase the perception of pungency of capsaicin and vice versa (Green, 1986), as well as the cooling sensation produced by menthol. By adding fat to food, the pungent sensation of capsaicin and menthol can be reduced, presumably due to the fact that fat probably interferes with the binding of capsaicin and menthol to the TRPV1 and TRPM8 channels (Allison *et al.*, 2001). For more information please refer to the excellent reviews on temperature and nociception by Green (2004), and on nociceptors and nociception by Woolf and Ma (2007).

2.5 THERMAL PERCEPTION

2.5.1 Thermal sensation

The body's core temperature varies by only a few degrees under normal conditions. Even slight increases in the core temperature lead to hyperthermia and if the set-point is changed, fever. Equally, a decrease of just a few degrees in core temperature results in hypothermia, where the body's metabolism and other functions become affected. In contrast, oral temperature and skin temperature can vary considerably depending on the environment we are in and what we eat or drink. Humans can discriminate temperatures ranging from very cold (–10 °C) to intense heat (60 °C) (Lumpkin and Caterina, 2007) and our lips and tongue exhibit a high sensitivity and can detect rapid fluctuations of small changes in temperature (Prinz *et al.*, 2007). Thermal sensations result from differences in temperature between the air surrounding us, or the objects we touch and the temperature at the level of the receptors. Hence, thermal receptors respond to changes in temperature. Small changes in skin temperature are perceived as warm or cool, but we adapt quickly to these sensations. Adaptation of thermal sensation can be observed over a relatively wide temperature range. With decreasing stimulus temperatures the quality of sensation may change from cool, cold, icy to painful. Similarly, stimuli of increasing temperature cause sensations of warmth, heat and pain.

2.5.2 Thermoreceptors

The receptors sensing innocuous (harmless) temperatures are sensitive to cold and warm stimuli. These thermal receptors are embedded in the terminals of afferent fibres which end as free nerve endings in the skin. The sensations of warmth and cold are mediated through the activity in dedicated primary afferents, that is warm and cold fibres. The warm fibres are active at temperatures between 30 °C and 48 °C, while the cold fibres are active at temperatures in the range 17 °C to 40 °C (Goldstein 1996). At moderate skin temperatures, such as 35 °C, both warm and cold receptors may be active. However, as the skin is warmed, the cold receptors stop firing and conversely, as the skin is cooled, the warm receptors become inactive. Most cold and warm receptors also stop firing altogether as the temperature extends into the noxious (damaging) range (below 5 °C and above 50 °C) (Gardner *et al.*, 2000). At these stimuli temperatures, humans perceive freeze and heat pain rather than sensations of cold and warmth. However, some cold fibres can also be activated by high temperatures in the noxious range (Campero *et al.*, 2001), and this may be the basis for the paradoxical cold sensation that can be elicited by stimulation with noxious heat stimuli. Thermoreceptors have small receptive fields and are slowly adapting, although they also discharge phasically when skin temperature is changing rapidly. Warm fibres are C-fibres, conducting on average at 1 m/s (LaMotte and Campbell, 1978), whereas cold fibres are suggested to be either thinly myelinated A δ , with conducting velocities of 9–15 m/s in monkeys (Darian-Smith *et al.*, 1979), or C-fibres (Schepers and Ringkamp 2010). For more information see Caterina's (2007) and Schepers and Ringkamp's (2010) extensive reviews on the topic.

2.5.3 Thermal transduction

Over the last decade strong evidence has emerged to support the contribution of TRP channels to peripheral temperature sensation. Several TRP channels from the TRP ion channel superfamily are equipped to detect thermal changes. Three TRP families, the TRP vanilloid channels (TRPV), the melastatin TRP channels (TRPM), and the ankyrin (TRPA) are of particular interest as thermoreceptors. Each of these receptor channels operates over a specific temperature range, thereby providing a potential molecular basis for thermosensation. The full range of temperatures, from noxious cold to noxious heat, appears to be transduced by the activity in these ion channels.

Warm stimuli activate TRPV3 and TRPV4 channels. Cold stimuli (below 26 °C) as well as menthol and other cooling agents activate the TRPM8 channel, suggesting that it mediates the detection of cold thermal stimuli. TRPM8-deficient mice show loss of sensitivity to cold stimuli and menthol; importantly, however, their behavioural responses to noxious cold temperatures (<12 °C) is only slightly affected (Bautista *et al.*, 2007), hence the TRPM8 channel is involved in thermal perception, but seemingly not in high-threshold nociception. When entering the range of noxious stimuli, TRPV1 and TRPV2 are activated by noxious heat and the TRPA1 channel transduces noxious cold stimuli (Schepers and Ringkamp, 2010).

While the discovery of thermosensitive TRP channels has greatly enhanced our understanding of transduction mechanisms of thermal stimuli, findings in animals with selective gene deletions indicate that multiple and as yet unknown transduction mechanisms are engaged by thermal stimuli. Hence, even though the TRP channels seem to be major

players in the transduction of thermal stimuli, there is more to it: it has been suggested that it is the constellation of various thermally sensitive proteins (TRP channels and various voltage-sensitive channels) together in a neuron that gives rise to a thermal receptor (Viana *et al.*, 2002). Some of the thermosensitive TRP channels respond not only to thermal stimuli, but to chemical and mechanical stimuli as well. TRPV4 has been reported to play a role in mechano-transduction (Liedtke 2007), and is also activated by hypotonic stimuli (Alessandri-Haber *et al.*, 2003), suggesting that it may also be a sensor for mechanical stretch and osmolarity. TRPV2 can also be activated by membrane stretch and hypotonic stimulation (Muraki *et al.*, 2003), and TRPV1 can be activated by protons (Tominaga *et al.*, 1998), hence it is likely that these TRP channels act as polymodal receptors.

Temperatures in the range to which the thermoreceptor is sensitive cause changes to the structure of the channel, leading to altered gating. Hence, when a thermal receptor (say, TRPV3) comes into contact with a warm stimulus, the shape of the channel protein changes and ion channels are opened, leading to the initiation of an action potential. This action potential is then propagated along the afferent fibre and follows the trigeminal pathway, see Figure 2.1.

2.5.4 Temperature and food

The temperature of the food and drink ingested can be very important for its acceptance. Coffee is mostly preferred either hot or cold, not lukewarm, while ice-cream is preferred cold. This is something that can be observed for many types of food and drink. Yet again, other products such as cookies or fruit are well appreciated at room temperature. These variances in preferred ingested temperature is probably due to flavour profiles which change with changing temperature, as well as changes in the physical characteristics of food, such as melting of jelly at high temperatures and the separation of fat-containing sauces upon cooling.

The fact that the face and particularly the lips contain more temperature-sensitive spots than most other regions of the body, suggests that the temperature of the food entering the mouth is well sensed. This will most certainly have an important input to the overall perception of food. Temperature of the mouth and food interact strongly with each other. Due to the rich vascularisation of the mouth, it functions well as a heat exchanger and oral parts can easily be heated or cooled depending on the temperature of the food. These changes in temperature will in turn also physically affect the food of subsequent bites. In a study in our laboratory (Engelen *et al.*, 2003), the oral temperature was manipulated by oral rinses of different temperatures. By rinsing with the mouth water at 10°C and 55°C for 5 s, the oral temperature was decreased to 27°C and increased to 43°C, respectively. These changes in temperature subsequently affected the way the food was perceived, and the attributes related to melting and smoothness were particularly affected. The perception of the temperature of an object or food seems to depend on the rate of heat transfer at the level of the thermal receptors. In an attempt to demonstrate this in the oral cavity, Prinz *et al.* (2007) asked subjects to rate the temperature of different food stuffs at different temperatures. They showed that higher fat products were sensed as less warm at higher temperatures and less cold at lower temperatures than their low-fat counterparts.

2.5.5 The thermoreception and nociception relation

Thermoreception and nociception have been proposed as an integrated modality to provide the afferent signal for homeostatic function and conscious perception of the condition of the body (Craig, 2003). Both thermal sensation and nociception seem to have multi-modal aspects and to be strongly interrelated. An example of this is the sensitivity of the same transduction receptors to heat and capsaicin (pungent – mild form of pain, and in higher concentrations – pain). Many people experience sweat droplets protruding on the forehead when eating hot/spicy food. This is due to the fact that capsaicin activates heat and pain channels that signal to the brain that hot items have entered the system. As a result, the brain receives a false signal that body temperature has risen and that there is a need for the body to dispose of the excessive heat. This initiates the chain of physiological events that leads to the sweating of the face, head and facial area. The sweating results in a cooling action, which is beneficial in a hot climate. The fact that we call the food ‘hot’ is a clear sign that the two modalities of temperature and pain are intermixed in our perception, hence capsaicin and other pungent substances can cause confusion to the body’s thermal sensation. Another example is the previously mentioned cooling effect of menthol transduced by the cold receptor TRPM8. Both the thermoceptive and nociceptive systems are protective in their function, but also add to the construct of the item we are touching or sampling in our mouth.

2.6 OLFACTION

2.6.1 Olfaction and food

The odour of food is of greatest important for its appreciation, identification and measure of safety. Walking in to a bakery makes us feel peckish almost instantaneously. When smelling food, the digestive system revs up to get ready to handle the food to be ingested. This odour-induced cephalic phase response includes increased salivary and gastric acid secretion. Olfaction plays an important part in determining the freshness and safety of food as well as in the overall perception of food. That is why, even though not strictly about oral receptors, I have chosen to include olfaction in this chapter.

The olfactory system reacts to airborne stimuli, called odorants. These tend to be lipid soluble and relatively small so that they can vaporise and be carried in the air. Odorants enter the nose and reach the nasal cavity either orthonasally, through the nostrils, as when sniffing a food, or retronasally, from the mouth via the pharynx, while ingesting food. The nose is a very sensitive chemodetector; it recognises odorous compounds at concentrations as low as a few parts per trillion (Breer, 2008).

Olfaction is a synthetic sense in that it is the combination of several odorants that produces an odour, for example the smell of freshly baked bread. Since the system is primed in this way, we are not very good at separating out the odour components of a mixture. The analytical part of olfaction can be enhanced by training, at least up to a certain level. Livermore and Laing (Livermore and Laing, 1996) demonstrated that even experts were having difficulties discriminating and identifying more than three odour components in a mixture of five. Similar results have been found for taste mixtures (Marshall *et al.*, 2005). We can discriminate thousands of odours and, with training, people have been found to be able to discriminate 100 000 odours. However discrimination is not equal to recognition,

and identification of odours is even more difficult. We are not used to describing smells (Ackerman, 1990) and there are very few words that are used to describe smells exclusively. Often words from other senses are used, such as sweet, warm or green (Auvray and Spence, 2008).

2.6.2 Olfactory receptors and transduction

Humans sense odorants by means of Olfactory Receptor Neurons (ORNs) located in the olfactory epithelium, in the roof of the nose. The ORN is a bipolar neuron; with two processes arising from either pole. One process is a thin unmyelinated axon that connects to the olfactory bulb. From the other pole a dendrite arises that ends in a knob with 6 to 12 cilia. The olfactory cilia protrude into the layer of mucous in the nasal lumen. These cilia form a dense mat and are covered in a layer of mucous that absorbs odorants from the circulating air. The mucous layer contains high concentrations of small, soluble odorant-binding proteins (Pelosi *et al.*, 2006) (Ko and Park, 2008), that can shuttle hydrophobic molecules through body fluids and across cell membranes. The precise role of these proteins in olfaction is not understood, but they are expected to influence the interaction between odorants and their receptors. Odour transduction is initiated in the cilia as a result of the interaction of odorant molecules with specialised olfactory receptors (ORs) within the ciliary membrane. Out of the total of about 400 types of ORs expressed in human, it is thought that each ORN expresses only one (or at most a few) types of OR, even though the evidence for this is limited (Mombaerts, 1999). All ORNs expressing the same type of receptor converge onto the same glomerulus pair in the olfactory bulb (Mombaerts *et al.*, 1996).

Odour receptor nerve cells function like a lock and key system: If the odorant can fit into the lock, the nerve cell will respond. However, it is more complex than the old model of one odorant, one receptor one smell (Amoore, 1970; Moncreiff, 1949). Each odorant activates a set of different olfactory receptors, and generates a unique pattern across the glomeruli. This unique pattern, the 'signature', is three dimensional, since a given odorant would bind to some receptors more strongly than to others to create a height dimension as well. Differences in these patterns generate different perceived odours. In addition, each receptor type is able to bind a large number of different odorants. In this way the limited number of ORs (ca 400 in human) can still detect a close to unlimited number of odorants. It operates efficiently with a set of broadly tuned sensors which, collectively, produce unique signal patterns for each stimulus. The brain is responsible for processing the combined signal into an interpreted smell.

In 1991 Buck and Axel (Buck and Axel, 1991) published the discovery of a large family of G-protein-coupled receptors (GPCRs) in mice used for olfaction. When the odorant has bound to the OR, the receptor undergoes structural changes which activate a G-protein. The G-protein mediates cAMP production, which in turn induces opening of ion channels allowing an influx of Ca^{2+} ions. The elevation of Ca^{2+} concentration opens chloride channels causing a further depolarising efflux of chloride ions sufficient for excitation (Kurahashi and Yau, 1993). This untypical reaction is based on the unusually high intracellular Cl^- concentration in olfactory neurons (Kaneko *et al.*, 2004). The action potential is carried through the olfactory nerve to higher brain centres. The axons of the ORN pass through the cribriform plate to synapse on the glomeruli in the ipsilateral olfactory bulb. Neurons from the olfactory bulb project directly to the olfactory cortex in the forebrain, including the pyriform cortex, amygdala and the entorhinal area. Many of these structures form the

limbic system, an ancient region of the brain concerned with motivation, emotion and certain kinds of memory. These areas then project to several other brain structures including the hippocampus, thalamus, hypothalamus and neocortex. It is only at this level that conscious perception of odours presumably takes place. Olfaction is the only sensory system to have this immediate access to the forebrain, and the strong association of odours and vivid memories stems from this synapse in the memory centre prior to central processing in the thalamus.

2.7 CONCLUDING REMARKS

In this chapter I have presented an overview of the receptors present in the oral and nasal cavities, and how they are important in the processing and perception of food. It is clear that the systems are very complex and a lot more research is needed to elucidate the mechanisms and functions, but it is also clear that oral receptors are of greatest importance for the ingestion, perception and appreciation of food.

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3 Role of Saliva in the Oral Processing of Food

Guy Carpenter

3.1 INTRODUCTION

Saliva coats all surfaces in the mouth and should, in theory, play a role in every aspect of food processing. In this chapter the role saliva does play in most food processing will be examined and so will those areas where it doesn't. Some topics (e.g. lubrication) may be treated more lightly if explored in other chapters in this book. Although widely regarded as an inert medium, saliva's protein and ion components changes a fluid that is 99% water into a solution with properties very unlike water (see Figure 3.1). These properties allow it to mediate the many functions of oral homeostasis at rest and during food processing. For long periods of the day (and night) saliva functions to prevent desiccation, abrasion and sticking together of mucosal surfaces. Once coated onto the soft and hard tissues of the mouth, saliva must constantly prevent the growth and invasion of harmful microorganisms and to maintain a suitable environment for taste buds to optimally detect tastants. Following the placement of food in the mouth saliva must perform different roles. Foods (solids and semi-solids) need to be broken up to be assessed by taste and smell (by the formation of aerosols that are detected in the nose), smoothness and other rheological measurements to ensure quality and detection of poisonous components. After approximately 5–10 chews, during which saliva also prevents the abrasion/cracking of teeth, the saliva-coated food particles are formed into a bolus ready to be swallowed. After swallowing, saliva performs a vital function in clearing the oral cavity of residual food. This reduces the availability of sugars and nutrients that could support growth of microorganisms that continually inhabit the oral cavity. If these organisms are not checked they can lead to dental caries and loss of teeth. Perhaps the best example of the importance of saliva in many food processes can be observed in patients with oral dryness caused by disease- or drug-induced, reduced salivary flow. These patients typically have problems tasting foods (most are too rich/strong), chewing, swallowing and often have rampant caries (Benaryeh *et al.*, 1985; Dawes, 2004; Mese and Matsuo, 2007; Young *et al.*, 2001). Before considering how saliva works to perform these different functions its secretion, composition and interaction with the oral mucosa is first considered.

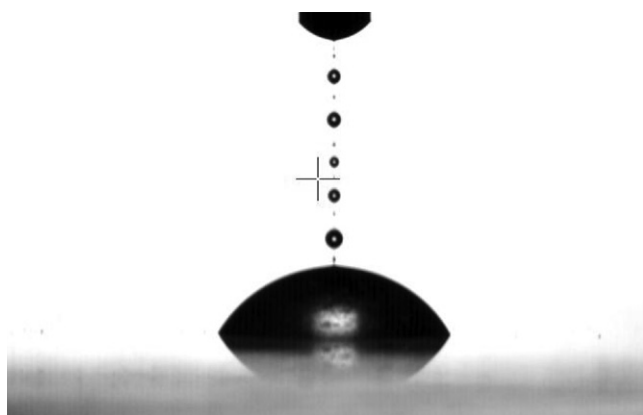


Figure 3.1 Saliva is a highly viscoelastic fluid, which when stretched displays ‘beads on a string’ morphology as characterised in a recent article (Reproduced from Bhat *et al.*, 2010 with permission).

3.2 CONTROL OF SALIVARY SECRETION

Salivary secretion is a reflex mostly stimulated by taste and chewing (Chaudhari and Roper, 2010; Hector and Linden, 1999). Resting, unstimulated salivary flow (approximately 0.5 ml/min) is the result of low levels of autonomic stimulation by the higher centres of the brain acting via the salivary centre on salivary glands (Matsuo, 1999). When we are asleep this higher centre input for resting salivary secretion is reduced and so we have decreased salivary flow (approximately 0.1 ml/min). Likewise during times of stress the higher centres reduce nerve traffic to the salivary centres (and then to the salivary glands) which causes a dry mouth (Garrett, 1987).

Salivary secretion is upregulated above the resting rate by taste and chewing and to a lesser degree by smell stimulation. Chewing of foods stimulates the receptors in the periodontal ligament (Scott *et al.*, 1998, 1999) sandwiched between the tooth and the alveolar process of the jaw bone, although interestingly these are not stimulated by empty chewing, that is teeth grinding (Anderson *et al.*, 1996). For taste stimulation of salivary secretion many studies have used citric acid as it generates by far the largest salivary flows – often at a tenth of the concentration of other stimulants; sweet, sour, bitter or umami (Hodson and Linden, 2006). However, citric acid is rarely apparent in the diet (in a non-buffered form) and thus chewing can be considered equally efficient at stimulating saliva production as taste under normal conditions. Since the taste, chewing and smell cues are integrated in the brain and then signals sent to the salivary glands, there are few differences in the protein profile between chewing and taste stimulated salivas, at least from the parotid gland. Although the submandibular/sublingual saliva does show variations in mucin concentration and other proteins between a chewing and taste stimulated secretion (see Figure 3.2) this probably reflects differential secretion by the two glands. Few studies collect a truly ‘pure; submandibular or sublingual secretion due to the difficulties of the ductal anatomy, as discussed below. More detailed proteomic analyses have revealed differences in the protein content of parotid saliva when stimulated by the different tastes (Neyraud *et al.*, 2006) although the proteins identified appeared to be principally of non-salivary gland origin.

It is thus well established that the main stimulants of salivary flow, above the resting rate, are taste and chewing, but surprisingly there is little evidence that the thought of food

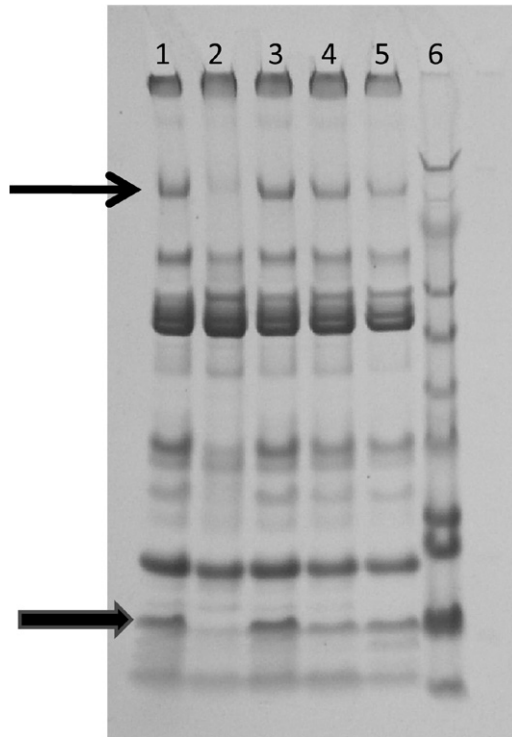


Figure 3.2 SDS-PAGE of submandibular/sublingual saliva collected during different stimulus conditions. Lane 1; sitting at rest, lane 2; smelling a beef smell (gravy), lane 3; visual images of food, lane 4; chewing tubing, lane 5; tasting citric acid, lane 6; molecular weight standards. Upper arrow indicates the mucin MG2 (MUC 7 gene product) and the lower arrow indicates statherin.

can affect salivary secretion. The occurrence of mouthwatering at the sight or thought of food, although widely appreciated, is a difficult one to reproduce under controlled conditions. Most experiences of food include an aroma that, as indicated above, can stimulate the submandibular/sublingual gland to secrete saliva. However, in some recent experiments by the author, when the smell component is removed no stimulated salivary secretion could be measured when subjects were exposed to food (by sight alone). Although some reports have shown a conditioned-like salivary reflex (Holland and Matthews, 1970; Jenkins and Dawes, 1966) the flows were very small and transient. In dogs and other species a conditioned salivary reflex can easily be demonstrated. A possible explanation for mouthwatering in humans would be the effect of facial muscles, under voluntary control, squeezing on the ducts conveying the saliva from the glands to the mouth to cause a transient flow of saliva (Carpenter and Ilangakoon, in prep.).

Of the major glands the parotid is the largest and contributes the greatest flow (as much as 60% of the total) when stimulated by taste or chewing (Matsuo, 2000). It secretes a serous secretion containing no mucins but rich in amylase and proline-rich proteins, the functions of which will be discussed later. Studies in rats indicate that the parotid gland is the most responsive to variations in the diet (Hall and Schneyer, 1964; Schneyer *et al.*, 1986). The submandibular and sublingual glands secrete a mucin-rich saliva in response to taste and chewing but also smell (Lee and Linden, 1992a) unlike the parotid which does



Figure 3.3 There are hundreds of minor salivary glands located all over the mouth. The minor glands in the lower lip are most readily accessible. After drying the labial surface and waiting 10 minutes, small beads of saliva become apparent, each corresponding to a minor salivary gland. Although innervated by parasympathetic fibres they are not generally thought to increase their secretory rate with stimulation by taste, chewing or smell. These labial glands are mucous, as are most in the mouth, the exception being the von Ebner's glands in the mucosa of the tongue which are serous.

not (Lee and Linden, 1992b). Often the submandibular and sublingual salivas are considered together since the ductal openings (Wharton's and Bartholin's respectively) both enter the mouth on a ridge under the tongue but in addition may, in some subjects, join together within the submucosa (Harrison J.D., 2010).

In addition to the major salivary glands (which exist as bilateral pairs) there are hundreds of minor salivary glands located in the submucosa throughout the oral cavity (see Figure 3.3). These glands secrete small volumes (< 1 ul/min/gland) of mucin-rich saliva and are generally considered not to become upregulated (i.e. no response to food) in the same way as the major glands. Although only contributing around 10% of salivary flow these glands are important in maintaining a mucin-rich layer adjacent to the mucosa. A small subset of the minor glands are the von Ebner's glands at the base of crypts surrounding the foliate and circumvallate (but not fungiform) papillae. These infrequently studied glands (Eliasson and Carlen, 2010) appear more serous than mucous and contain some proteins of interest to food processing, such as lipocalin and lingual lipase. However their output is so small that their role can only be to maintain their immediate environment, that is the taste buds.

The secretion of saliva is a well studied mechanism, for a review see Turner and Sugiya, 2002, that involves the active secretion of salt (as chloride ions) by the acinar cells into the ductal lumen of the gland. Water, derived from the blood system, passes around (via the tight junctions) and through (via aquaporin channels) the acinar cells to form a saliva that is isotonic with respect to serum. In the parotid and submandibular glands the salt is mostly recovered by the striated ducts – which are impermeable to water. Their 'striated' description derives from their corrugated basal membrane which is packed with mitochondria. Recovery of salt from the saliva changes the primary isotonic saliva (as secreted by the acini) into a hypotonic saliva. This has important implications for the maintenance of taste buds and their sensitivity to salt detection (Matsuo, 2000). By maintaining the taste buds

in a hypotonic saliva taste buds are able to detect salt at much lower thresholds than found in serum. However the reabsorption of salt is an energy expensive process (hence the large numbers of mitochondria within the striated ducts) which is not upregulated during stimulated salivary secretion – the result is that stimulated saliva has a higher sodium and chloride concentration than resting saliva.

A second adaptation of resting saliva for greater taste sensitivity is a lower buffering capacity compared to stimulated saliva. Saliva is buffered mostly by bicarbonate ions and carbonic anhydrase, which catalyses the combination of bicarbonate and protons to water and carbon dioxide. The effect of reduced buffering is a greater sensitivity to acidic or sour-tasting substances which are sometimes indicative of inedible foods, such as milk, but can be perceived as refreshing, such as citrus.

Several other proteins and components are present in lower amounts and may play roles in improving the detection of certain tastants. Proline-rich proteins (PRPs), for example, are known to interact with the tannins involved in astringency, if saliva principally acts as a barrier (discussed later) to protect the mouth structures then a reduced PRP concentration in resting saliva would again enhance the ability to perceive astringency.

As well as the different glands contributing saliva at different rates into the mouth, each gland also has a different profile of proteins (see Figure 3.4). Some proteins are universal to all glands, such as secretory component, the transporter of IgA (the main antibody in saliva). Mucins (Muc 5b and Muc 7 gene products) are common to the submandibular,

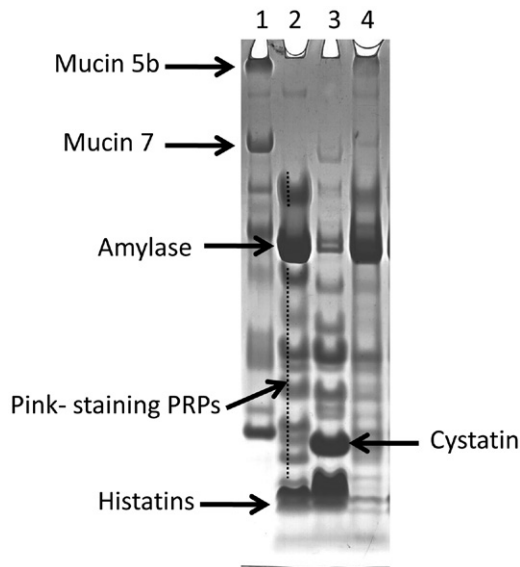


Figure 3.4 Electrophoretic separation of salivary proteins from different glands. SDS-PAGE separates proteins according to size, and if stained by Coomassie Brilliant Blue R250 colours proline-rich proteins metachromatically pink. Lane 1; minor saliva, lane 2; parotid saliva, lane 3; submandibular/sublingual saliva, lane 4; whole mouth saliva. Major proteins are indicated, the dotted line in lane 2 indicates proline-rich proteins. Whereas parotid saliva is predominated by amylase and proline-rich proteins, minor and submandibular/sublingual saliva have mucins (Muc 5b and Muc 7). It is interesting to note that although all glands empty into the mouth, whole mouth saliva is not always the sum of the parts, presumably because proteins have bound to different surfaces in the mouth.

sublingual and most minor glands but are not expressed by the serous glands – parotid and von Ebner’s glands. Basic PRPs appear to be exclusive to the parotid glands whilst acidic PRPs appear in submandibular and parotid glands. PRPs are highly polymorphic and, whilst only encoded by 6 genes, over 50 different proteins exist, mostly due to gene rearrangements but also to some post-secretory processing (Azen, 1993). The result of this is a huge variety of proteins varying not only between people but also within the same individual at different times of the day (due to the contribution of different glands).

3.3 FUNCTIONALITIES OF SALIVA

The functions of saliva in the mouth can be simply related to the two types of surfaces found in the normal healthy mouth – teeth and mucosa. Although there are some functions common to these surfaces, such as microbial homeostasis and lubrication (see Figure 3.5), most functions are specialised for each surface. Thus for the hard tissues, maintaining a high calcium and phosphate environment is important to prevent dental erosion – teeth slowly dissolve in water. Whereas for the soft tissues other functions are required, some (taste) relate to food and will be discussed later. The growth, healing and hydration of the mucosa reflects the trophic effects of saliva on the mucosa and is well demonstrated in dry-mouth patients who have atrophic mucosa and reduced sensitivity of the taste buds (Matsuo, 2000). Saliva’s role in healing is demonstrated by the greater speed by which mucosal injuries heal, some recent reports indicate the increased healing is caused by specific salivary proteins (Oudhoff *et al.*, 2010) and some report the novel effects of catecho-

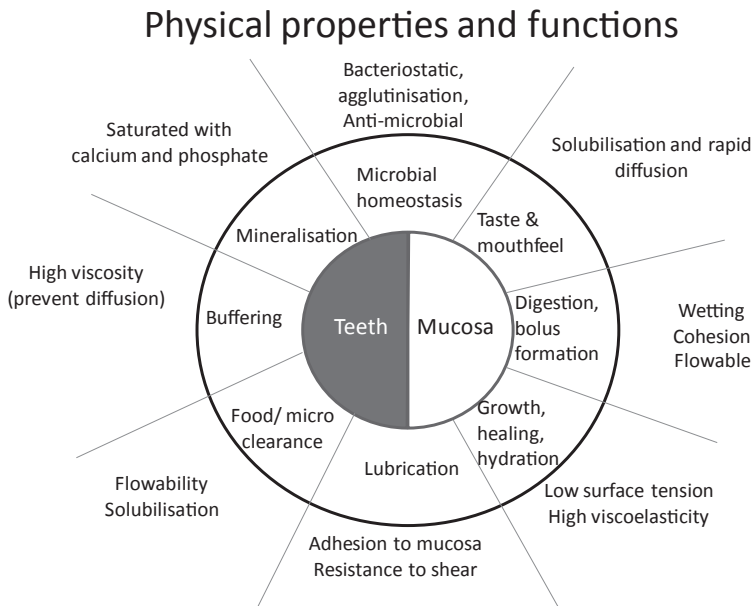


Figure 3.5 The physical properties and functions of saliva in the mouth are related to the two types of surfaces found in the normal healthy mouth – teeth and mucosa. Although there are some functions common to these surfaces, such as microbial homeostasis and lubrication, most functions are specialised for each surface.

lamines on oral keratinocytes (Steenhuis *et al.*, 2011). Interestingly, although epidermal growth factor (EGF) was first identified and extracted from salivary glands, (Cohen, 2004) there are relatively small amounts in human saliva and it probably has little impact on oral wound healing. Most research to date has focused on the anti-microbial effects of different salivary proteins. Current thinking suggests that saliva maintains a stable benign/beneficial ecosystem where the growth of potentially harmful microorganisms is kept in check by the promotion of other species. Many microorganisms can utilise the breakdown of salivary proteins, and in particular the glycans attached to proteins, to support growth. Most microorganisms are cleared from the mouth by the continuous flow of saliva. As with most of the functions identified in Figure 3.5, the physical properties of the saliva will have a great influence on how well it carries out functions. For clearance (of food and microorganisms) a low viscosity fluid would work best. Whereas for many of the protective functions of saliva, a more highly viscoelastic saliva would function better. How saliva manages to achieve both is by the formation of pellicles and multiple phases of saliva as outlined below.

3.3.1 Salivary interactions with the oral mucosa

Saliva exists in the mouth as a heterogeneous (Sas and Dawes, 1997), thin film (Pramanik *et al.*, 2010) that coats and interacts with the mucosa to form a highly lubricating layer (Bongaerts *et al.*, 2007). The structure of the oral mucosa varies from non-keratinised squamous cells in the buccal region to keratinised gingivae and papillae on the dorsum of the tongue (see Figure 3.6). The degree of keratinisation and the depth of the Rete processes reflect the mechanical abrasion (as a result of chewing and tongue movements) that occurs at those points. The thickness of the salivary film varies from 5 µm on the hard palate to 25 µm on the tongue, as calculated by measuring the amount of saliva per unit area (Pramanik *et al.*, 2010). The thickness of saliva in different areas of the mouth probably reflects a number of variables including local flow rates, the salivary viscoelastic properties and the surface roughness of the mucosa. The dorsal surface of the tongue, for example, has the thickest film probably because of the papillae forming pronounced ridges. On the hard surfaces in the mouth salivary proteins readily and specifically interact with the mineral components of teeth. The acquired enamel pellicle (Dawes *et al.*, 1963) is a subset of salivary proteins that rapidly bind to calcium phosphate salts within teeth mostly via a post-translational modification of the protein, that is a phosphate group. The most abundant salivary proteins in acquired enamel pellicles include statherin, acidic proline-rich proteins and histatins (Jensen *et al.*, 1992; Li *et al.*, 2004). Modelling teeth with hydroxyapatite, mucins were also found to form strongly lubricating layers (Cardenas *et al.*, 2007; Hahn Berg *et al.*, 2003; Halthur *et al.*, 2010). The presence of statherin, a calcium carrier, enhances the local concentration of calcium around teeth and thus prevents dissolution of teeth (Hay and Bowen, 1999). The other proteins presumably play a role in managing the microflora that also bind to teeth.

As well as the enamel pellicle there is also evidence of a mucosal pellicle, that is a select group of salivary proteins that are bound, to varying degrees, to oral mucosal cells. Initial observations (Bradway *et al.*, 1989; Bradway *et al.*, 1992) suggested that mucins, amylase, cystatin S and acidic PRPs were present. The absorption of mucins to any surface in the mouth would be important for lubrication (Stokes and Davies, 2007). Once absorbed, the film might be modified by the ionic composition of saliva. In a study of absorbed mucins to control surfaces mimicking the oral mucosa, the absorbed mucin layer was found to vary in thickness between a low and high ionic strength solution (e.g. resting versus stimulated

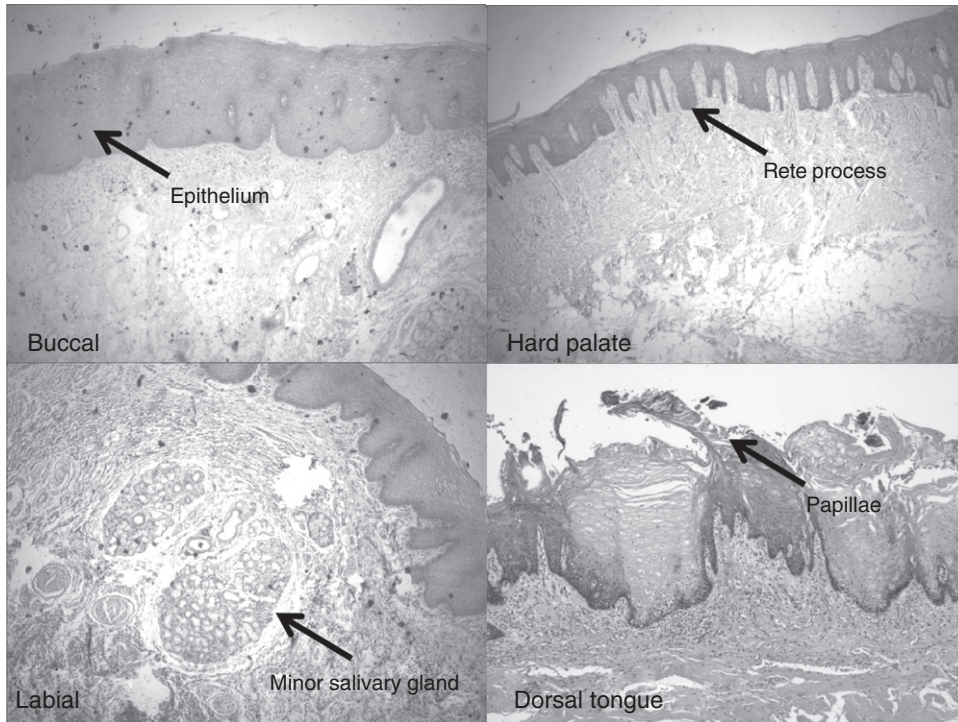


Figure 3.6 Variations in the oral mucosa from different locations within the mouth. The epithelium lies on top of the lamina propria and the submucosa. At some locations, such as the hard palate, the Rete processes penetrate further into the lamina propria and resist the effects of abrasion. In the labial surface a submucosal salivary gland is apparent. The tongue has keratinised papillae separated by normal epithelium.

saliva). This mucin film collapsed in a completely deionised environment, suggesting static repulsion between molecules can influence film hydration/thickness (Macakova *et al.*, 2010). It would be interesting to know whether the salivary film ever collapses *in vivo*. A study of dry-mouth patients indicated that the salivary film was still present but thinner (Pramanik *et al.*, 2010) perhaps suggesting a collapse of the mucosal pellicle leading to the loss of lubrication and feelings of dryness. Riding over these pellicles (enamel and mucosal) flows the fluid phase of saliva. The flow starts from the openings of the ducts leading from the major glands (sublingual and buccal areas) and travels over all surfaces, at varying speeds, towards the throat for swallowing (or spat out). This flow of saliva is important for the clearance of food and bacteria from the mouth and so maintains a normal healthy mouth.

3.3.2 Perception of taste

Resting saliva, as noted above, is ideally modified to assist the initial tasting of foods. It has a low salt content as the low flow rate allows the striated ducts to reabsorb most of the sodium and chloride ions changing the primary saliva, which is initially isotonic with serum, into a hypotonic solution. It also has a low buffering ability since the secretion of

both bicarbonate ions and carbonic anhydrase is related to flow rate. The low surface tension, which is a feature of resting and stimulated saliva allows a rapid interaction of the tastant with taste buds. For many tastants, such as salt and acids, saliva will be the solvent used to convey the ions to the taste buds. It is surprising then that an aqueous solution, such as saliva, is readily able to detect tastes locked up in an oil/fat liquid. The interaction of oil in water emulsions stabilised by different emulsifiers is a subject of considerable interest. Oil is well known to become emulsified by saliva, probably by interaction with the mucins (Silletti *et al.*, 2007). The deposition of oil onto the tongue surface, studied by both *in vivo* confocal microscopy (Adams *et al.*, 2007) and simpler paper sampling methods (Pivk *et al.*, 2008) again relates to the emulsifying behaviour of saliva. Further interactions of emulsions stabilised with different proteins reveals that the nature of the interaction with the oral mucosa governs taste and the mouthfeel of the food (Vingerhoeds *et al.*, 2008, 2009). Whey protein-stabilised emulsions did not readily interact with the tongue and formed creamy type sensations, whereas lysozyme-stabilised emulsions formed almost astringent-like sensations and remained on the tongue.

3.3.3 Protection of the oral environment

During the mastication of foods saliva performs a series of different functions in protecting the mouth from both the food (or its components) and from the actions of breaking up the food, that is chewing forces. To protect teeth from dissolution in acidic environments and from abrasion, salivary proteins bind to teeth to form the enamel pellicle. Once food is in the mouth, salivary production is stimulated and the buffering capacity greatly increases, from the greater secretion of bicarbonate ions and carbonic anhydrase. No similar mechanisms appear to protect the mouth from foods that are too bitter, salty or sweet; presumably because in small quantities these components are beneficial to the host. However, there does appear to be a mechanism to protect the mouth and alimentary canal from tannins. Tannins are naturally occurring secondary metabolites of some plants and are found in the human diet, in greatest amounts in (green or black) tea and red wines. Although adding an interesting astringent sensation when consumed, in larger quantities tannins are harmful since they bind up enzymes and proteins necessary for the normal uptake of nutrients (Manach *et al.*, 2005). Salivary proteins histatins and proline-rich proteins (PRPs), which make up nearly 70% of all parotid salivary protein (Kauffman and Keller, 1979), bind very well to dietary polyphenols/tannins (Baxter *et al.*, 1997; Bennick, 2002; Wroblewski *et al.*, 2001). The high affinity of these proteins to tannins is thought to have a protective effect since animals that lack proline-rich proteins do not survive on high tannin diets (Mcarthur *et al.*, 1995). Although dietary polyphenols can cause tooth-staining (Carpenter *et al.*, 2005; Proctor *et al.*, 2005b) it is their role in causing astringency that generates most interest. Astringency, at least at low levels, adds refreshment to a drink. Although tannins are known to interact with salivary proline-rich proteins and histatins it is not understood how this leads to a dry, puckering sensation of the entire mucosa. A common view is that astringency is due to the loss of lubrication of the salivary film. Recent studies suggested that whilst there is a loss of interfacial rheology of saliva following interactions with polyphenols (Rossetti *et al.*, 2008) it could not account for the astringency of all astringent compounds tested. The possible interaction of proline-rich proteins already bound to buccal cells, as part of the mucosal pellicle, was explored in a recent report by the author (Nayak and Carpenter, 2008). We speculated that if proline-rich proteins and histatins are involved in astringency then washing the mouth out with water (to reduce the levels of these proteins)

prior to the ingestion of a tannin solution should reduce the perception of astringency. In fact, astringency increased. This reinforces the view that saliva acts principally as a barrier to astringency. Analysis of the proteins precipitated by the tannin solution after several oral rinses revealed proline-rich proteins and mucins, previously adherent to the mucosa. This would suggest that any food/chemical that disrupted this adherent layer of protein would cause an astringent feeling. Detergents, such as sodium/ lauryl sulphate, metal ions such as copper (Hong *et al.*, 2009) or whey proteins (Vardhanabhuti *et al.*, 2010) can all cause astringent sensations without obvious interactions with, or precipitation of, salivary proline-rich proteins. Hence the continued search for mechanisms underlying the physiology of astringency.

3.4 SALIVA IN BOLUS FORMATION, SWALLOWING AND ORAL CLEARANCE

3.4.1 Bolus formation and swallowing

The ability of humans to swallow foods appears to be a learnt process whereas the swallowing of liquids is innate (Thexton *et al.*, 2007). Modelling of the swallowing process has found two factors that seem to correspond to the optimum moment to swallow: particle size, which relates to hardness of food and the break-up qualities of the food, and the lubrication properties of the bolus relating to the salivary covering of the food particles. Incorporation of saliva into the bolus is not necessary for many drinks to be swallowed, but the coating of food particles to form a bolus is (Prinz and Lucas, 1997). Exactly what physical characteristic of saliva contributes to bolus formation is poorly studied; one possible area would be the viscoelastic qualities of saliva, which are often related to the mucin components. However the wettability of the saliva, which relates to surface active components, must also be important, especially for dry hydrophobic foodstuffs. The salivary components that create the wettability of saliva are again unknown (Ranc *et al.*, 2006) but may relate to statherin, which is a highly surface-active protein (Proctor *et al.*, 2005a). In the mouth, where the mucosa is already coated in a salivary layer, coating of the food particles in saliva helps prevent the adherence of food to the mucosa. In dry-mouth patients food sticking to the mucosa is a common complaint (Benaryeh *et al.*, 1985) and shows that the mucosa is intrinsically hydrophobic (see Figure 3.7). Formation of a bolus is mainly driven by voluntary tongue movements, whereas the pharyngeal and oesophageal phases are regulated by the autonomic nervous system (Lang, 2009).

3.4.2 Post-mastication oral clearance

Clearance of food stuffs from the mouth is vital to contain the growth of potentially harmful microorganisms already colonising in the mouth. The problem is clear in individuals with regular or high-sugar diets which are frequently associated with widespread dental caries. Dental caries is the erosion of tooth enamel by (principally lactic) acid produced by bacteria feeding off free sugars within the mouth. Clearance of food debris left over following chewing is therefore an important objective to maintain the structural integrity of teeth. A study of children with cleft palate, who have higher rates of caries than controls, clearly demonstrated the effect of reduced oral clearance (Ahluwalia *et al.*, 2004). As well as the dynamic effect of salivary flow over surfaces (Sas and Dawes, 1997) and the mechanical



Figure 3.7 Effects of a dry mouth. Oral mucosa appears to be inherently hydrophobic and ‘sticky’ when a lubricating layer of saliva is not present. This leads to problems of food sticking to surfaces, abrasion and difficulty swallowing. Water or even salivary substitutes are poor at mimicking the complex viscoelasticity of saliva.

action of the tongue (de Wijk *et al.*, 2009), there are also at least two enzymes, amylase and lipase, that contribute to oral clearance. Amylase is the single most abundant protein in parotid saliva and a prominent component of whole mouth saliva. The genetics of amylase has been particularly well studied (Novembre *et al.*, 2007). It has a specificity for converting maltose to glucose, although it will convert multimers of glucose subunits to glucose (Koyama *et al.*, 2000). In saliva it exists as several isoforms – mostly in the glycosylated form; the salivary amylase gene is separate to the pancreatic gene (Bank *et al.*, 1991). Even though there are plentiful supplies of amylase in the mouth it would appear that amylase has a limited role in the tasting or even the digestion of starchy foods (Butterworth *et al.*, in prep.; Prinz and de Wijk, 2007) although some have tried to link amylase to diet in primates (Mau *et al.*, 2010). Initial studies by Engelen and colleagues suggested a role for amylase in the breakdown of starch-based custards. The addition of water, saliva or an amylase solution to custard prior to consumption showed an effect, notably on ‘melting’ characteristics (Engelen *et al.*, 2003). Furthermore these effects were not present if an amylase inhibitor or a non-starch base were used (de Wijk *et al.*, 2004). However it has to be accepted that these effects may be peculiar to custards and not so relevant to all starch-based foods. So what then is the role of the copious quantities of amylase in the mouth? Its binding of carbohydrate may confer bacterial binding properties (Scannapieco *et al.*, 1993) and thus may have an influence on the control of caries, although few studies have shown a strong link. A study of six foods suggested the persistence of measureable amounts of glucose and lactic acid (produced by plaque bacteria) for up to an hour following ingestion (Linke and Birkenfeld, 1999). Interestingly there was little difference in glucose or lactic acid production between the starchy foods (such as bread and chips/fries) and a chocolate bar.

Lingual lipase is an enzyme peculiar to the specialised minor salivary glands in the pits surrounding the circumvallate and foliate papillae, in which most taste buds are located. These are unusual minor glands as they are serous in nature (rather than mucous) and their secretory products more closely resemble the parotid glands rather than the sublingual

glands (Azen *et al.*, 1990; Isola *et al.*, 2010). Despite being described as serous, the von Ebner's glands have two proteins which are not expressed in the parotid glands, lipocalin (a.k.a. von Ebner's gland protein) and lingual lipase. Although lipocalin is part of a super-family of lipo-philic molecules (Grzyb *et al.*, 2006) that have a function in detecting aromas, including fatty acid smells (Stopkova *et al.*, 2009) their potential role for delivering fats to the taste buds (Gilbertson, 1998) is not as clear. A study investigating whether the mouth and nose were able to distinguish three different fatty acids revealed that whereas the nose could, the mouth could not (Bolton and Halpern, 2010). Since the von Ebner's glands are a small proportion of all minor glands, which as a total only make up less than 10% of all salivary flow, it is safe to assume that these glands do not contribute to any significant degree to fat digestion. Instead, the role of these proteins is more likely to maintain a suitable environment for the taste buds. Since emulsions are known to deposit significant quantities of oil on the surface of the tongue (Adams *et al.*, 2007), one role for lingual lipase would be to remove oil from the surface of the tongue to enable subsequent tasting (Dresselhuys *et al.*, 2008).

3.5 CONCLUDING REMARKS

The linking up of salivary proteins to specific processes or functions has always been difficult because most, if not all, salivary proteins are multifunctional. Whereas many salivary proteins have been shown to bind bacteria, few proteins have been linked to taste (Nieuw Amerongen and Veerman, 2002). Frequently, gustin is cited in reviews and textbooks, following a report of its alteration in patients with altered taste (Henkin *et al.*, 1999) but few reports have followed it up and it is more likely to reflect a metabolic lack of zinc and thus unlikely to mediate taste in normal individuals. The challenge still exists to know how salivary proteins interact with food components to mediate taste and mouthfeel effects. Some excellent work is being undertaken on the interactions of emulsions with saliva and mucosal surfaces. It would be exciting to see similar work in other areas of food processing, such as aerosol formation properties of saliva to enhance flavour.

If genetic differences between groups of individuals do decide if certain foods are appealing or distasteful (Sandell and Breslin, 2006) one wonders if similar changes occur in salivary proteins to mediate alterations in taste between individuals. Acquiring a taste for bitter-containing foods is often related to age and may relate to taste receptor polymorphisms (Mennella *et al.*, 2010). Salivary proteins are also known to change with age, so could the two be linked? Due to the complexity of saliva it will be challenging to link up behavioural traits (e.g. the avoidance of certain foods) to specific features of saliva, but if possible this will yield important information on a fundamental part of life.

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Part Two

Food Oral Management

4 Oral Management of Food

Andries van der Bilt

4.1 INTRODUCTION

Chewing is the first step in the process of digestion and is meant to prepare the food for swallowing and further processing in the digestive system. In the mouth, the food is subjected to several mechanical and chemical processes. Taste and texture of the food are perceived and have their influence on the chewing process. The water in the saliva moistens the food particles, whereas the salivary mucins bind masticated food into a coherent and slippery bolus that can be easily swallowed.

In Section 4.2 oral factors determining the chewing result are introduced. Characteristics of the oral system, such as dentition, bite force and salivary flow rate will influence the masticatory process, that is the size reduction of food particles, salivation and mixing of food particles into a food bolus that can be swallowed. Section 4.3 deals with the influence of food characteristics on chewing. Food hardness affects masticatory force, jaw muscle activity and movements of the lower jaw. The number of chewing cycles needed to prepare a food for swallowing depends on the hardness and dryness of a food. In Section 4.4 an overview of the neuromuscular control of chewing and swallowing is presented. The movement of the jaw, and thus the coordination between the various chewing muscles, plays an important role in the fragmentation of the food.

4.2 FACTORS INFLUENCING ORAL FUNCTION

Chewing, talking, laughing, smiling and yawning are important functions of the oral system. Dentition, tongue, cheeks, lips, jaw muscles, neuromuscular control and saliva are essential to perform these functions adequately. Numerous studies have been performed to quantify various oral factors in order to get an impression of the functioning of the mouth. All ingested solid foods, regardless of bite size and initial texture, are processed in a stereotyped way by humans (Hiimeae *et al.*, 1978; Thexton, 1992; Thexton and Crompton, 1998; Hiimeae and Palmer, 1999; Hiimeae, 2004; German *et al.*, 2004; Okada *et al.*, 2007). After ingestion the food is transported from the front of the mouth to the occlusal surfaces of the post-canine

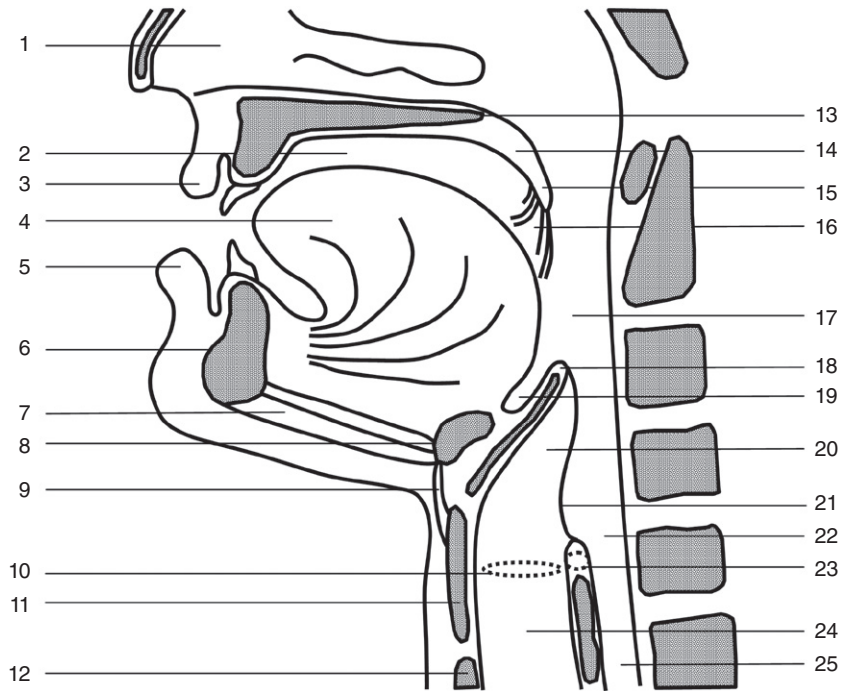


Figure 4.1 A schematic overview of the anatomical structures of oral cavity and pharynx. 1. nasal cavity, 2. oral cavity, 3. upper lip, 4. tongue, 5. lower lip, 6. mandible, 7. m. geniohyoideus and m. mylohyoideus, 8. hyoid bone, 9. m. thyrohyoideus, 10. true and false vocal folds, 11. thyroid cartilage, 12. cricoid cartilage, 13. hard palate, 14. soft palate, 15. uvula, 16. palatopharyngeal folds, 17. pharynx, 18. epiglottis, 19. valleculae, 20. laryngeal vestibule, 21. aryepiglottic fold, 22. upper oesophageal sphincter, 23. arytenoid cartilage, 24. trachea, 25. oesophagus.

teeth (stage I transport). A schematic overview of the anatomical structures of the mouth and pharynx is given in Figure 4.1 and an overview of stage I transport in Figure 4.2.

The food is processed by a series of masticatory cycles needed to comminute and soften the food (food processing stage). Large food particles are broken down between the (pre) molar teeth into small pieces, which are mixed with saliva to form a food bolus. Digestive enzymes act on the masticated food and salivary mucins bind the food particles into a coherent and slippery bolus that can easily slide through the oesophagus without damaging the mucosa (Pedersen *et al.*, 2002). The number of processing cycles increases as foods become more difficult to chew. When food is ready to be swallowed it is propelled posteriorly into the oropharynx (stage II transport). Food accumulates in the oropharynx until it is finally swallowed (Hiemae and Palmer, 1999). A schematic diagram of the mechanism of stage II transport is given in Figure 4.3.

The initiation of swallowing, which is voluntary, has been thought to depend on separate thresholds for food particle size and for particle lubrication (Hutchings and Lillford, 1988). However, instead of this duality, it has also been suggested that swallowing is initiated when it is sensed that a batch of food particles is bound together under viscous forces so as to form a bolus (Prinz and Lucas, 1997). The first phase of swallowing is also called the oral or clearing phase. It is under voluntary control and typically takes less than one second to complete (Logemann, 1983). Practically all the intrinsic and extrinsic muscles of the

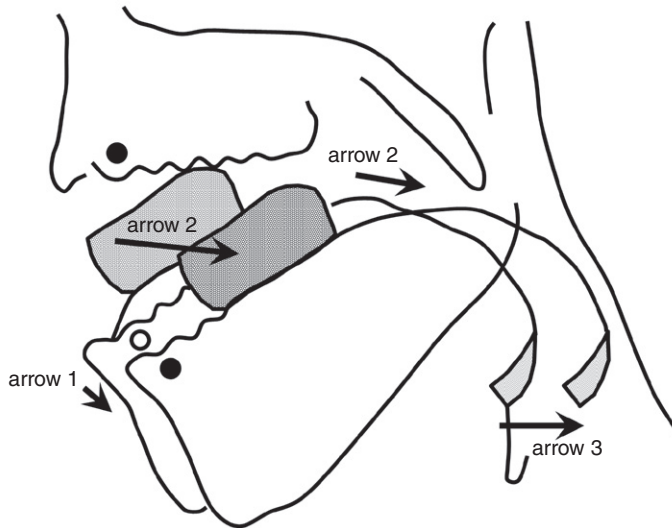


Figure 4.2 Stage I transport. A piece of solid food is deposited on a slightly elevated tongue surface. As the jaw opens a little more (1.), the tongue surface drops below the occlusal plane of the lower post-canine teeth and is pulled sharply backwards with the hyoid (2.). The lumen of the pharynx is almost obliterated (3.). The 'pull-back' was followed by elevation and rotation of the tongue bringing the food into position on the molars ready for tooth-food-tooth contact and the first power stroke. Reproduced from Karen Hiimeae, 2004, pp.171–200, with permission from John Wiley & Sons.

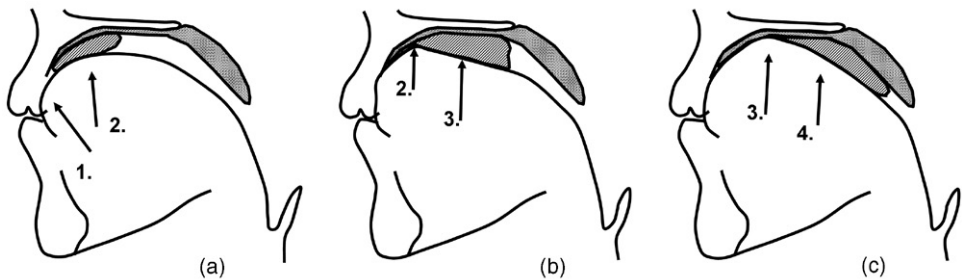


Figure 4.3 Stage II transport. (a) The initial tongue movement involves its surface rising to contact the hard palate just behind the incisors (1); the anterior tongue continues to expand compressing the food on the anterior palate and starting to force it backwards (2). (b) The tongue surface is now in extensive contact (2) with the anterior hard palate, the food bolus has been squeezed backwards with its leading edge approaching the fauces (3). (c) The tongue–palate contact has travelled posteriorly towards the posterior hard palate (3) and the food is passing through the fauces (4). Reproduced from Karen Hiimeae, 2004, pp.171–200, with permission from John Wiley & Sons.

tongue, and the suprahyoid muscles, are active as the food bolus is positioned in the middle of the tongue. The tongue helps to propel the bolus to the pharynx through an anterior to posterior rolling action, with tongue elevation, distal squeezing against the hard palate and contraction of the pharyngeal constrictor muscles (Logemann, 1983). The palatopharyngeal folds are pulled medially to form a slit through which properly masticated food can pass.

As the bolus passes the anterior palatopharyngeal folds, the oral stage of the swallow is terminated and the swallowing reflex is triggered (Logemann, 1983). As the swallow begins, respiration is reflexively inhibited (Morrell, 1984). The second phase of swallowing, the pharyngeal phase, is entirely elicited by reflexes. The pharynx elevates and contracts followed by a peristaltic wave movement of the musculature in a caudal direction, so that the food bolus descends into the oesophagus. Simultaneously, the larynx elevates and moves anteriorly, thereby contributing to laryngeal closure. The epiglottis is folded down to cover the entrance of the laryngeal vestibule and the trachea during swallowing, so that the lower respiratory tract is protected from the entry of saliva or food particles, while they pass through in the pharyngeal phase (Ertekin *et al.*, 2001; Pedersen *et al.*, 2002). The third phase of swallowing is the oesophageal phase, which involves a sequential contraction of the oesophagus. This phase is also controlled by reflexes (Thexton, 1992). Oesophageal peristalsis carries the food bolus through the cervical and thoracic oesophagus into the stomach.

Characteristics of the oral system, such as dentition, bite force and salivary flow rate, will influence the masticatory process, that is the size reduction of food particles, salivation and mixing of food particles into a food bolus that can be swallowed. The number of chewing cycles needed to prepare food for swallowing (stage I transport until swallowing), defined here as the swallowing threshold or moment of swallowing, is rather constant within a subject for one type of food, whereas large variations in the number of chewing cycles until swallowing were observed among subjects (Lucas and Luke 1986; Fontijn-Tekamp *et al.*, 2004).

A way to quantify oral function is to determine how well persons are able to break down their food and how long individuals chew before they swallow their food. Besides direct measurements of oral function, indirect methods have also been widely used through interviewing individuals about their oral function. In this section methods will be discussed that have been used to describe and quantify oral factors and oral function.

4.2.1 Dental factors

Many people have deficiencies in oral function because of loss of teeth, malocclusion or periodontal disease. However, despite their handicap, most people manage to eat successfully even though they are unable to comminute their food perfectly before swallowing. Declining masticatory function due to compromised dentition is responsible for swallowing poorly chewed food (Hildebrandt *et al.*, 1997; Fontijn-Tekamp *et al.*, 2004). Furthermore, compromised masticatory performance results in consumption of predominantly soft, easy to chew foods. This may induce poor dietary practices and marginal nutritional intakes (Sheiham *et al.*, 2001; N'Gom and Woda, 2002; Bartali *et al.*, 2003; Roininen *et al.*, 2004; Walls and Steele, 2004; Sakurai *et al.*, 2005; Bradbury *et al.*, 2008). In order to improve the masticatory function, missing teeth are often replaced by fixed or removable prosthodontic appliances. Indeed, a clear relationship exists between dental state and masticatory performance as determined from chewing tests (Helkimo *et al.*, 1978; Feldman *et al.*, 1980; Luke and Lucas, 1985; Omar *et al.*, 1987; Akeel *et al.*, 1992; van der Bilt *et al.*, 1994; Hatch *et al.*, 2000). People wearing complete dentures have difficulty with breaking down

food. Their masticatory performance is very poor as compared to that of people with natural dentition. Food pulverisation experiments have shown that complete denture wearers have a much lower masticatory performance than persons with natural dentition. Complete denture wearers needed on average four times the number of chewing strokes of dentate persons to achieve the same degree of pulverisation (Manly and Braley, 1950; Fontijn-Tekamp *et al.*, 2000; van Kampen *et al.*, 2002a). Mandibular implant overdenture treatment is a successful treatment modality for complete denture wearers (Fueki *et al.*, 2007). The maximum bite force of subjects with a mandibular denture supported by implants was 60 to 200% higher than that of subjects with a conventional denture (Lindquist and Carlsson, 1985; Haraldson *et al.*, 1988; Carlsson and Lindquist, 1994; Fontijn-Tekamp *et al.*, 1998; van Kampen *et al.*, 2002b). The masticatory performance also significantly improved after implant treatment (Geertman *et al.*, 1994; Pera *et al.*, 1998; Fontijn-Tekamp *et al.*, 2000; Bakke *et al.*, 2002; van Kampen *et al.*, 2004; Stellingsma *et al.*, 2005). The number of chewing cycles needed to halve the initial size of a test food on average decreased from 47 to 25 cycles after implant treatment (van Kampen *et al.*, 2004). Thus, after implant treatment, subjects needed only about half the number of chewing cycles as before treatment to comminute their food to a certain size.

4.2.2 Jaw muscle activity (EMG) and bite force

Chewing requires muscle activity to make the movements of the jaw and to exert forces in order to cut or grind the food. The amount of muscle activity has been shown to depend on the texture of the food: more muscle activity is observed for harder foods (Mathevon *et al.*, 1995; Agrawal *et al.*, 1998; Mioche *et al.*, 1999; Peyron *et al.*, 2002). The amount of muscle activity is an indication of how forcefully a subject can chew or clench the teeth together.

Maximum voluntary bite force is an important variable to assess the functional state of the masticatory system. Bite force has been used to evaluate oral function in relation to, for example, occlusal factors (Bakke *et al.*, 1990; Tsuga *et al.*, 1998), dentition (Miyaura *et al.*, 1999; Gibbs *et al.*, 2002), dental prostheses (Helkimo *et al.*, 1977; Slagter *et al.*, 1993b), and implant treatment (Carlsson and Lindquist, 1994; Fontijn-Tekamp *et al.*, 1998; van Kampen *et al.*, 2002b). Bite force has been reported to have a large influence on masticatory performance in subjects with overdentures, full dentures as well as natural dentitions (Fontijn-Tekamp *et al.*, 2000; Hatch *et al.*, 2000). Correlation coefficients up to 0.8 were reported, and thus bite force explains over 60% of the variance in masticatory performance.

Significantly higher maximum bite forces are reported for men than for women (Bakke *et al.*, 1990; Waltimo and Könönen 1993; Fontijn-Tekamp *et al.*, 1998; Ferrario *et al.*, 2004; Ikebe *et al.*, 2005; van der Bilt *et al.*, 2008). Average maximum voluntary bite forces of 490 N (men) and 418 N (women) were recently reported (van der Bilt *et al.*, 2008). Maximum bite force tends to decrease with age for adult subjects (Helkimo *et al.*, 1977; Bakke *et al.*, 1990; Miyaura *et al.*, 1999; Hatch *et al.*, 2000; Gibbs *et al.*, 2002; Ikebe *et al.*, 2005; van der Bilt *et al.*, 2008). The decrease in bite force may be a direct effect of age on muscle strength or it may be caused by changes in food choice because of deteriorated dentition. This may lead to less trained jaw muscles. Although the correlation between age and bite force is significant, it should be realised that the effect of age on bite force is small. Correlation coefficients between -0.22 and -0.31 were reported, which means that age explains less than 10% of the variance of bite force. In a study on the determinants of

masticatory function it was reported that age had a direct effect on bite force as well as an indirect effect on bite force, which was caused by a decrease in the number of occlusal units with increasing age (Hatch *et al.*, 2000).

4.2.3 Masticatory performance

Masticatory function can be described in terms of the objective capacity of a person to fragment solid food or as the subjective response of a person to questions concerning chewing food. Objective masticatory function (defined as masticatory performance) has often been measured by determining an individual's capacity to grind or pulverise a test food. Several studies have shown that masticatory function is reduced in people who have lost postcanine teeth (for example Helkimo *et al.*, 1978; Feldman *et al.*, 1980; Käyser, 1981; Luke and Lucas, 1985; Omar *et al.*, 1987; van der Bilt *et al.*, 1993a; van der Bilt *et al.*, 1994), and in those who wear removable dentures (for example Kapur and Soman, 1964; Helkimo *et al.*, 1977; Slagter *et al.*, 1993a). Implant-supported prostheses improve the oral function and satisfaction in edentulous patients (for example Geertman *et al.*, 1994; Kapur *et al.*, 1998; Tang *et al.*, 1999; Fontijn-Tekamp *et al.*, 2000; van Kampen *et al.*, 2002b). Subjective masticatory function (defined as masticatory ability) has been studied by interviewing subjects on their oral function (for example Agerberg and Carlsson, 1981; Käyser, 1981; Wayler and Chauncey, 1983; Chauncey *et al.*, 1984; Oosterhaven *et al.*, 1988; Witter *et al.*, 1990; Sarita *et al.*, 2003; Johansson *et al.*, 2007; Ueno *et al.*, 2008; Bradbury *et al.*, 2008). The subjective evaluation of masticatory performance includes other aspects of mastication such as adaptational and psychological factors that cannot be obtained from pulverisation tests (Agerberg and Carlsson, 1981; Akeel *et al.*, 1992).

The rate of breakdown of food depends on many anatomical and physiological variables. Study of the comminution of solid food is of interest in revealing the relative importance of these variables to masticatory performance. A wide variety of methods have been used to analyse chewing performance, for example measuring colour change in chewing gum (Matsui *et al.*, 1996; Hayakawa *et al.*, 1998; Ishikawa *et al.*, 2007), sugar loss from chewing gum (Heath, 1982), a colourimetric method to determine the release of dye when chewing raw carrots (Käyser and Hoeven, 1977), photometric methods to quantify changes in colour (Masuda *et al.*, 1981; Gunne, 1983; Nakasima *et al.*, 1989), and optical scanning of chewed particles (Shi *et al.*, 1990; van der Bilt *et al.*, 1993b). However, in the majority of the studies on chewing performance the degree of breakdown of a food has been determined by sieving the comminuted food (for example Manly and Braley, 1950; Edlund and Lamm, 1980; Lucas and Luke, 1983; Olthoff *et al.*, 1984; van der Bilt *et al.*, 1993a; Fontijn-Tekamp *et al.*, 2000). Both natural foods, such as peanuts, almonds and carrots, and synthetic materials have been used as test materials in experiments determining the masticatory performance. A natural test food has the advantage that it is normally consumed, so that subjects are accustomed to it. However, the consistency of the food may vary due to seasonal and geographical influences. To avoid these variations in consistency, artificial food is a good alternative, which has often been used (for example Edlund and Lamm, 1980; Olthoff *et al.*, 1984; Slagter *et al.*, 1993a; Fontijn-Tekamp *et al.*, 2000).

Another method to determine masticatory performance, which is now widely used, evaluates the ability to mix and knead a food bolus. Two-coloured chewing gum (Liedberg and Öwall, 1995; Prinz, 1999; Schimmel *et al.*, 2007; van der Bilt *et al.*, 2010) and paraffin wax (Sato *et al.*, 2003a; Salleh *et al.*, 2007; Sugiura *et al.*, 2009; Speksnijder *et al.*, 2009) have been used as test foods for the quantification of masticatory performance. The degree

of mixing of the two colours was determined by optical methods (for example Prinz, 1999; Sato *et al.*, 2003a; Speksnijder *et al.*, 2009) or by visual inspection, for example (Liedberg and Öwall, 1995). Validity and reliability studies showed that chewing on two-coloured wax paraffin is a reliable alternative for comminution tests (Sato *et al.*, 2003b; Speksnijder *et al.*, 2009). It was concluded that the mixing ability test is more suitable for, and discriminates better between, persons with compromised masticatory performance than the comminution test (Speksnijder *et al.*, 2009).

4.2.4 Swallowing of food

The number of chewing cycles needed to prepare food for swallowing (stage I transport until swallowing), defined here as the swallowing threshold or moment of swallowing, is rather constant within a subject for one type of food, whereas large variations in the number of chewing cycles until swallowing were observed among subjects (Lucas and Luke, 1986; Fontijn-Tekamp *et al.*, 2004). For instance, the number of chewing cycles needed to swallow 9.1 cm³ of peanuts varied between 17 and 110 in a group of 87 dentate subjects (Engelen *et al.*, 2005). Furthermore, the moment of swallowing appeared to be strongly correlated among various natural foods (Fontijn-Tekamp *et al.*, 2004). This means that subjects who used a small number of chewing cycles for one food consistently also used small numbers for all types of food. This implies that there are 'slow' and 'fast' swallowers (subjects who swallow any food after a relative low or high number of cycles, respectively). This is partly the result of the individual's physiology, but possibly also of the social context. Figure 4.4 illustrates the large variation in chewing behaviour among people. The jaw movement, rectified muscle activity and muscle work (product of jaw gape and muscle activity) are shown for 2 healthy subjects (A and B). The subjects were instructed to chew and swallow a piece of bread (13 cm³). Subject A chewed 8 times on the bread and then swallowed it (upper 3 rows), whereas the second subject chewed the bread 34 times, thus more than 4 times longer, before he swallowed it (lower 3 rows). Figure 4.4 clearly illustrates that muscle work decreases while mastication proceeds and the food bolus is softened.

Although the number of chewing cycles needed to prepare the food for swallowing varies greatly among people, the moment of swallowing was shown to be only weakly correlated with the chewing performance (Fontijn-Tekamp *et al.*, 2004). Thus, a subject with a high masticatory performance does not necessarily swallow food after a smaller number of chewing strokes than a subject with a less high masticatory performance. This is illustrated in Figure 4.5. The number of chewing cycles needed to prepare the food for swallowing is plotted as a function of the masticatory performance (median particle size after 15 chewing cycles) for 87 subjects (Fontijn-Tekamp *et al.*, 2004). Low values of the median particle size (left part of figure) indicate that the food was well fragmented and thus the masticatory performance is good, whereas large values (right part of figure) indicate that the food was not broken into small particles (bad chewing performance). As can be seen from the Figure 4.5 there is no relation between the number of chewing cycles up to swallowing and the masticatory performance. As a consequence subjects with a high masticatory performance will, on average, swallow finer food particles (median particle size below 3 mm) than subjects with a less high performance (median particle size above 3 mm). This is illustrated in Figure 4.6, where the median size of the swallowed food is plotted as a function of masticatory performance (Fontijn-Tekamp *et al.*, 2004). A significant correlation between the median particle size of the bolus ready for swallowing and the masticatory

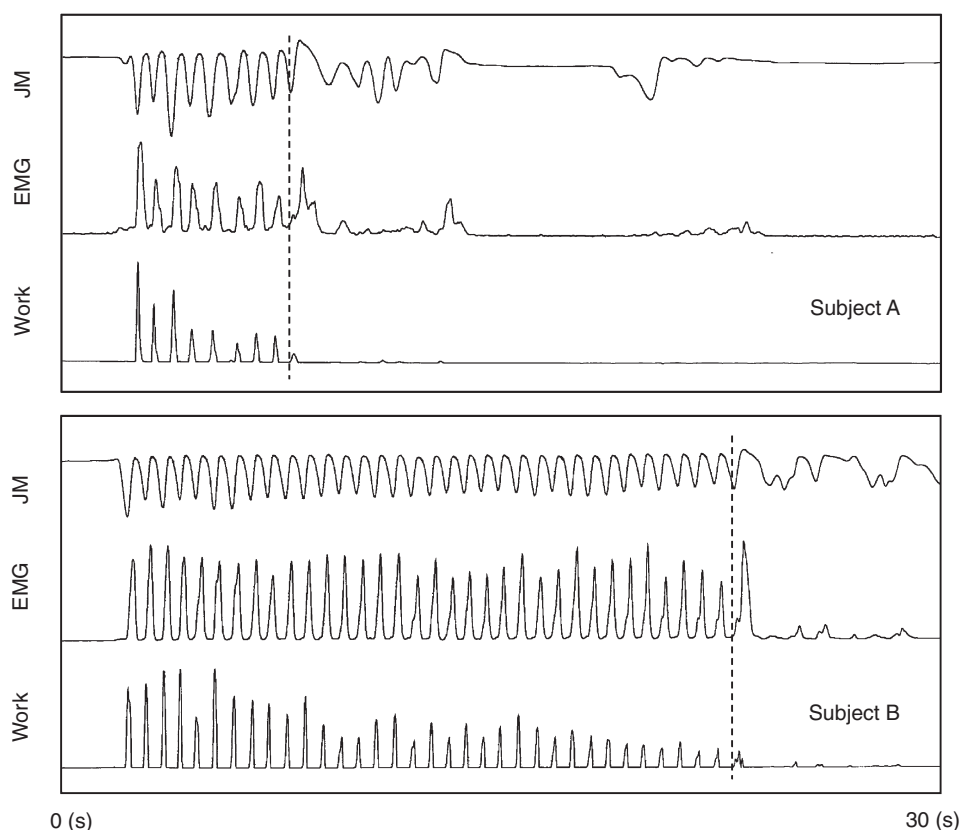


Figure 4.4 Jaw movement (JM), rectified muscle activity (EMG), and muscle work (work) of two subjects chewing a piece of bread (13 cm^3). EMG and work bursts occur while the jaw is closing. The work bursts decline while mastication proceeds and the food bolus is softened. The dashed lines indicate the moments before the food was swallowed. Subject B chewed the bread more than four times longer than subject A.

performance was observed ($r = 0.59$, $p < 0.001$). Similar results have been reported previously: persons with diminished ability to chew compensated for this dental handicap by swallowing larger particles of food (Yurkstas, 1965; Bates *et al.*, 1976; Carlsson, 1984; van der Bilt *et al.*, 1993a). Tooth loss significantly decreased the swallowing threshold performance and increased the particle size a subject was willing to swallow (Feldman *et al.*, 1980).

4.2.5 Saliva

The production of sufficient saliva is indispensable for good chewing. The water in saliva moistens the food particles, while the salivary mucins bind masticated food into a coherent and slippery bolus that can be easily swallowed (Pedersen *et al.*, 2002). It has been suggested that the swallowing process is initiated when the cohesive forces that bind food particles together into a bolus are strongest (Prinz and Lucas, 1997). The important role of saliva for chewing and swallowing is demonstrated by the finding that the number of chewing strokes, hence time in the mouth, needed for swallowing significantly increases

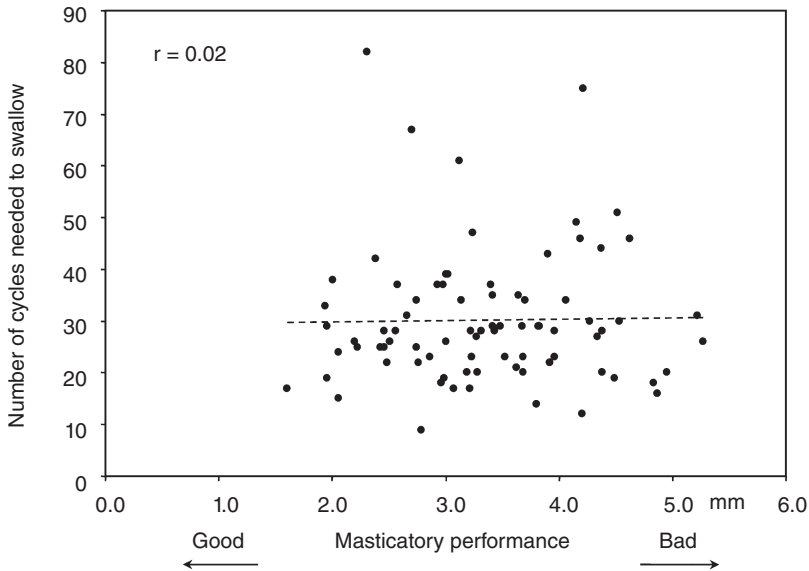


Figure 4.5 The number of chewing strokes needed before swallowing the test food (Optocal) as a function of the median particle size obtained after 15 chewing strokes (masticatory performance). The data were obtained from 87 healthy adult subjects. Dashed line shows linear regression. A very low correlation ($r = 0.02$) was observed, which indicates that there is no relationship between the number of chewing strokes until swallowing and the masticatory performance. Reproduced from Fontijn-Tekamp *et al.*, 2004, with permission from Elsevier.

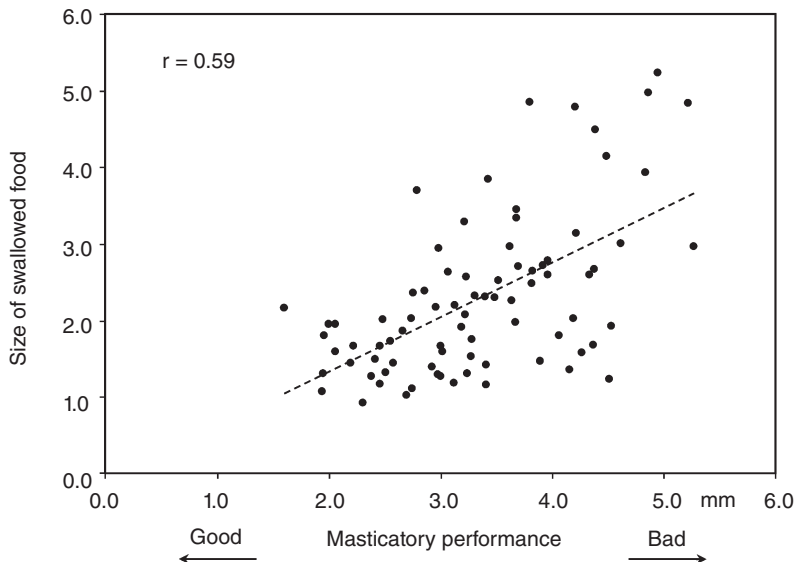


Figure 4.6 Median particle size of the swallowed food as a function of the median particle size obtained after 15 chewing strokes (masticatory performance). The data were obtained from 87 healthy adult subjects. Dashed line shows linear regression. A significant correlation ($r = 0.59$; $p < 0.001$) was observed, which indicates that subjects with a good masticatory performance swallow finer food particles than subjects with a less good performance. Note that the median sizes of swallowed food vary from 5.23 mm (hardly fragmented particles) down to 0.92 mm (very fine grains), which indicates the large differences in chewing behaviour among the 87 healthy subjects. Reproduced from Fontijn-Tekamp *et al.*, 2004, with permission from Elsevier.

after experimentally induced oral dryness (Liedberg and Öwall, 1991). Additionally, significantly more saliva is required for oral manipulation of powdered crisp bread than for pieces of crisp bread (Pangborn and Lundgren, 1977) as the larger surface area of the powder requires more saliva for lubrication and cohesive binding in preparation for deglutition. In a study on rabbits, it was demonstrated that greater amounts of saliva were produced for dry food than for moist food (Anderson *et al.*, 1985). The amount of saliva also plays a role in the chewing of meat, with more saliva being incorporated into a food bolus of tough meat, than into tender meat, before the bolus is swallowed (Mioche *et al.*, 2003).

While saliva and chewing have been shown to be interrelated, the relationship between amount of saliva and mastication has not been studied extensively (Hector and Linden, 1999). During mastication it is likely that mechanoreceptors in the gingival tissues will be stimulated which may result in salivary flow (Anderson *et al.*, 1996; Scott *et al.*, 1999). At chewing forces as low as 5% of comfortable chewing force the masticatory-salivary reflex could already be elicited (Anderson *et al.*, 1996).

Mechanically stimulated salivary flow rate can be determined in a standardised way from chewing on a piece of tasteless Parafilm. Over a period of 5 minutes a subject expectorates saliva at 30-s intervals into a pre-weighed container and flow rate (ml/min) is then calculated. In a group of 266 healthy subjects salivary flow rates ranged from 0.16 to 3.8 ml/min (Engelen *et al.*, 2005). In that study it was shown that the moment of swallowing was only weakly correlated ($r = -0.13$; $p = 0.04$) with the salivary flow rate of a subject. The results of that study are shown in Figure 4.7. Salivary flow rate only explains 2% of the variance in the swallowing threshold. This means that a subject with a relatively high salivary flow rate does not necessarily swallow food after fewer chewing cycles than a subject with less saliva. As a consequence subjects with relative high salivary flow rates are used to swallowing better moistened food than subjects with less saliva. Again this may influence the perception of the food. However, previous work in our laboratory has shown that there was no relationship between a subject's salivary flow rate and sensory ratings of semi-solids (Engelen *et al.*, 2003b). Thus, a subject with a larger salivary flow rate during eating did not rate food differently from a subject with less salivary flow. An artificial increase of 0.5 ml of saliva significantly influenced the sensory ratings of semi-solids (Engelen *et al.*, 2003a). The addition of a fluid affected the mouthfeel attributes of thickness and melting of vanilla custard dessert. The fact that the perceived effect was equally strong for water as for α -amylase solution and saliva, and that a larger fluid volume increased the effect is evidence that the decreased sensation was mainly due to dilution. For more information on saliva on texture perception, see Chapter 8 (Engelen and De Wijk), and on saliva and oral processing, see Chapter 3 (Carpenter).

The following review articles may be helpful in further study:

- Review article on Food oral processing (Chen, 2009).
- Review article on Assessment of mastication with implications for oral rehabilitation (van der Bilt, 2011).

4.3 INFLUENCE OF FOOD CHARACTERISTICS ON CHEWING

Physical properties of a food can be determined from rheological measurements. An important objective method to determine properties for solid foods is a compression machine and

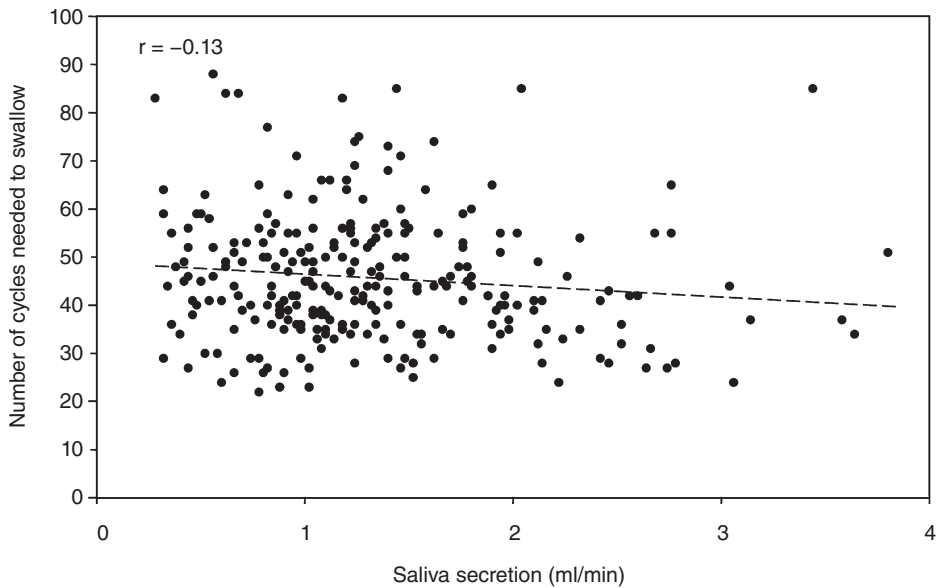


Figure 4.7 Number of chewing strokes needed before swallowing non-buttered melba toast as a function of the salivary flow rate. The data were obtained from 266 healthy adult subjects. Dashed line shows linear regression. A small, but significant correlation was observed ($r = -0.13$; $p = 0.04$; 2% explained variance only), which indicates salivary flow rate does not influence the swallowing threshold. Reproduced from Engelen *et al.*, 2005, with permission from Elsevier.

for liquid foods a rotary viscometer. Universal testing machines can be set up to use a number of different test procedures, including deformation, puncture, extrusion, cutting-shear and crushing (Bourne, 2004). With such a machine force-deformation curves (stress-strain curves) can be obtained. In texture profile analysis (TPA) bite-size pieces of food are compressed and decompressed two times, imitating the first two chews on a food (Bourne, 2002). This procedure allows the determination of, for example, fracturability (force at a significant break in the first bite), and hardness (maximum force of first bite) of a food sample. Solid food can also be characterised by textural parameters, such as hardness (soft, firm, hard), cohesiveness (crumbly, crunchy, brittle), viscosity (thin, viscous), springiness (plastic, elastic), and adhesiveness (sticky, gooey) (Szczeniak, 2002). Furthermore, solid food has geometrical characteristics: size, shape and orientation of particles (e.g. gritty, grainy, course, fibrous). Other characteristics of food are moisture and fat content (dry, moist, wet; oily, greasy). It should be noted that texture is a sensory attribute and therefore only people can really measure texture (Bourne, 2004). The characteristics of a food may influence the masticatory process.

By understanding the processes in the mouth while eating, a better understanding of the sensations and the perceptions of the food can be gained. Knowledge of physiological parameters may be of importance when performing and designing rheological/instrumental measurements for a food. Better predictions of sensory perception of a specific food may thus be obtained. This could save time and money on time-consuming and expensive sensory panels in the earlier steps of product development and renovation. Knowing how

physiological processes highlight specific flavour/texture sensations may be useful for product development or quality control where one typically wants to focus on certain sensations and ignore others. In addition, a future application could be to tailor products for personalised nutrition, individual choices or clinical nutrition based on physiological groups.

4.3.1 Influence of food type on muscle activity, chewing force and jaw movement

The influence of food characteristics on the chewing process has been extensively studied. Food hardness is sensed during mastication and affects jaw muscle activity (Horio and Kawamura, 1989; Mathevon *et al.*, 1995; Agrawal *et al.*, 1998; Mioche *et al.*, 1999; Peyron *et al.*, 2002; van der Bilt *et al.*, 2007), masticatory force (Kohyama *et al.*, 2004) and jaw movements (Thexton *et al.*, 1980; Pröschel and Hofmann, 1988; Hiimeae *et al.*, 1996; Peyron *et al.*, 1997).

A clear relationship between food hardness and jaw muscle activity has been reported in numerous studies. Increased jaw muscle activity and longer duration of the muscle activity were observed for harder foods (Plesh *et al.*, 1986; Horio and Kawamura, 1989; Agrawal *et al.*, 1998; Mioche *et al.*, 1999; Peyron *et al.*, 2002; Foster *et al.*, 2006; van der Bilt *et al.*, 2007). It was shown that the hardness of chewing gum (soft or hard gum) influenced the chewing cycle duration and the amplitude of the muscle activity. The subjects chewed slower and with more muscle activity on the hard gum (Plesh *et al.*, 1986). In another study muscle activity was measured while subjects chewed on 15 different types of food (various kinds of cheeses, nuts and carrots), which largely varied in mechanical properties (Agrawal *et al.*, 1998). Young's modulus and toughness were measured for each food. Young's modulus (or elastic modulus) was determined from the slope of a force-deformation curve of the material. Toughness is the resistance to fracture of a material when stressed and was measured by a wedge test. Muscle activity needed to chew the various food types turned out to be highly significantly related to the square root of the ratio of toughness and the modulus of elasticity ($p < 0.0001$). The influence of food characteristics on chewing was also studied using model foods (Foster *et al.*, 2006). Two model food types were used, presenting either elastic or plastic rheological properties. Each model food type consisted of four products of different hardness. The elastic model food was an edible jellied confectionery product and the plastic model food was an edible caramel confectionery product. Muscle activity was significantly affected by an increase in hardness regardless of the food type. Chewing tests were also performed with meat of two different textures: tough and dry versus tender and juicy meat (Mioche *et al.*, 2003). The mean muscle activity needed for chewing the tough meat was significantly higher than for chewing the tender meat.

Chewing force has been measured using a multiple-point sheet-type sensor (Kohyama *et al.*, 2004). The sensor was a flexible sheet, thinner than 0.1 mm, which had many pressure sensing points (269 sensing cells) on it. Each sensing cell detects pressure in real time. With this method both chewing force and contact area between the teeth are obtained. Three silicone rubber model foods of varying hardness were used. The study clearly indicated that sample hardness modified chewing force of humans. The masticatory force during chewing samples of silicon rubber was shown to increase from 100 to 150 N, when the hardness of the samples increased by a factor of 2 (Kohyama *et al.*, 2004). Chewing force

was also determined for five natural foods in the first chew (Kohyama *et al.*, 2001). Force–time curves varied greatly for both foods and subjects. Various peaks occurred in the force–time curves of cracker and rice cracker, whereas only two peaks were observed for carrot. The authors suggested that the first peak corresponded to sample rupture.

Jaw movement was reported to be influenced by food hardness (Horio and Kawamura, 1989). Larger jaw openings were observed when subjects chewed on harder foods. Similar results were reported for edible model foods (Peyron *et al.*, 2002). Four gelatine-based visco-elastic foods identical in shape but differing in hardness were used. The amplitude of the mandibular movements increased for harder foods, especially in the first five chewing cycles.

4.3.2 Crispy food

When we chew a crispy food, the jaw decelerates and accelerates as a result of resistance and breakage of food particles and a characteristic sound of the breakage of the food particles is produced. The characteristic breakage behaviour of a food and the corresponding sound is essential for the sensory sensation. Crispness of a food is perceived through a combination of auditory, tactile, kinaesthetic and visual sensations (Duizer, 2001; Zampini and Spence, 2004). The crispy nature of food products is an important sensory characteristic on which consumers base their appreciation (Szczesniak, 2002; Roudaut *et al.*, 2002; Zampini and Spence, 2004; Chen *et al.*, 2005; Chaunier *et al.*, 2005; Spence and Zampini, 2006). Auditory cues play an important role in crispness perception as has been reported in numerous studies (Drake, 1963; Kapur 1971; Christensen and Vickers, 1981; Vickers, 1987; Seymour and Hamann, 1988; Lee III *et al.*, 1990; Dacremont *et al.*, 1991; Al Chakra *et al.*, 1996; Srisawas and Jindal, 2003; Zampini and Spence, 2004; Chen *et al.*, 2005; Chaunier *et al.*, 2005; Courcoux *et al.*, 2005; Varela *et al.*, 2008). If a crisp product does not produce the expected sound upon biting, then it is considered to be stale and of poor quality (Duizer, 2001). The sounds perceived during sensory evaluation of foods are transmitted to the inner-ear by both air and bone conduction (Drake, 1963; Kapur, 1971; Dacremont *et al.*, 1991; Dacremont, 1995). Receptors in the oral cavity sense characteristics of the food. The oral cavity is one of the regions of the body most densely innervated with nerve fibres and receptors and is exquisitely sensitive to tactile stimulation (Van Boven and Johnson, 1994). The somatic sensory system transmits information about touch, temperature, pain and proprioception (Engelen and van der Bilt, 2008). Proprioception is the sense of static position and movement of the limbs and body (Brooks, 1986). Visual cues such as colour, shine, grains and heterogeneity (lumps) provide information on the texture of the food. Visual cues play an important role in odour and flavour perception (Blackwell, 1995; Morrot, 2001; Zampini *et al.*, 2007), but vision was reported not to have an effect on auditory perception (Dacremont and Colas, 1993). Groups of blindfolded and sighted panellists similarly scored on the duration, loudness and pitch of biting sounds for various crispy foods.

4.3.3 Influence of food type and volume on swallowing

Food characteristics do have a large influence on the number of chewing cycles needed to prepare the food for swallowing (Hiiemae *et al.*, 1996; Mioche *et al.*, 2003; Engelen *et al.*,

2005; van der Bilt *et al.*, 2007; Jalabert-Malbos *et al.*, 2007). In a group of 87 dentate subjects the number of chewing cycles varied from on average 17 cycles for a portion of 8 cm³ of cake up to 61 cycles for an equal portion of carrots (Engelen *et al.*, 2005). The volume of the food also greatly influences oral physiology. For larger portion sizes, subjects needed more time and chewing strokes before they swallowed the food (Lucas and Luke, 1984; Gavião *et al.*, 2004; Fontijn-Tekamp *et al.*, 2004; Blissett *et al.*, 2007). The number of chewing strokes needed to prepare the food for swallowing linearly increased as a function of the food volume ($P < 0.001$) (Fontijn-Tekamp *et al.*, 2004). Sample thickness of the food also influences chewing. The force needed to chew a piece of apple increased with sample thickness (Dan *et al.*, 2003). Food size was shown to influence jaw movement: larger food sizes led to larger jaw gapes and larger jaw velocities during chewing (van der Bilt *et al.*, 1991; Miyawaki *et al.*, 2000). These results suggest that during chewing the jaw is opened to a level just large enough to place the food bolus between the molar teeth.

Dry and hard products required more chewing cycles before swallowing than moist and soft products. Evidently, more time is needed to break the food down and to add enough saliva to form a cohesive bolus suitable for swallowing (Anderson *et al.*, 1985). Thus, a dry product needs a longer time in the mouth to allow for enough secretion of saliva. Confirming this, buttering dry foods (cake, melba toast and toast) significantly reduced the number of chewing cycles of these foods (Engelen *et al.*, 2005). The reason for this is probably that butter enhances lubrication and bolus formation of dry products, decreasing the time needed in the mouth to form a coherent bolus. Similar results were observed in a study in which lubrication of the food bolus had been experimentally varied (Prinz and Lucas, 1995). In a recent study it was shown that adding small volumes of water (5 or 10 ml) to a food significantly lowered the number of chewing cycles and total muscular work until swallowing (Pereira *et al.*, 2006; van der Bilt *et al.*, 2007). Results from this study are depicted in Figure 4.8. The average muscle activity per chewing cycle is plotted versus the number of chewing cycles for five different foods. For each food three different conditions were measured: food without additional water, and food with 5 or 10 ml additional water. The additional water reduced the number of chewing cycles until swallowing and the muscle activity for melba toast, cake, peanut and cheese, but not for carrot. The largest effects were observed for melba and cake, which are dry products requiring sufficient saliva to form a coherent bolus safe for swallowing. More facilitation of the chewing process was observed after adding fluid to breakfast cake for subjects with relatively low salivary flow rates. Subjects with a relatively low salivary flow rate apparently benefit more from the addition of water than subjects with a larger flow rate.

Several texture and sound attributes of melba, cake and peanut were also significantly affected by the additional fluids (Pereira *et al.*, 2006; Dijksterhuis *et al.*, 2007). For melba, cake and peanut significant correlations between physiology parameters and several attributes for the various fluid conditions were observed. This indicates that adding a small volume of water to the food affects both the physiology (muscle activity and number of cycles) and the sensory perception of a number of texture and sound attributes.

In a recent article the particle size distributions of the food boluses suitable for deglutition and the number of chewing cycles until swallowing were determined for 10 natural foods (Jalabert-Malbos *et al.*, 2007). The number of cycles, sequence duration and particle size distributions significantly differed among subjects and foods. Large differences in average median particle size of the bolus ready to swallow were observed, ranging from 0.82 mm for peanuts (hard food) to 3.04 mm for gherkins (soft food). Foods that were rapidly swallowed were both soft and characterised by a high water content (egg white,

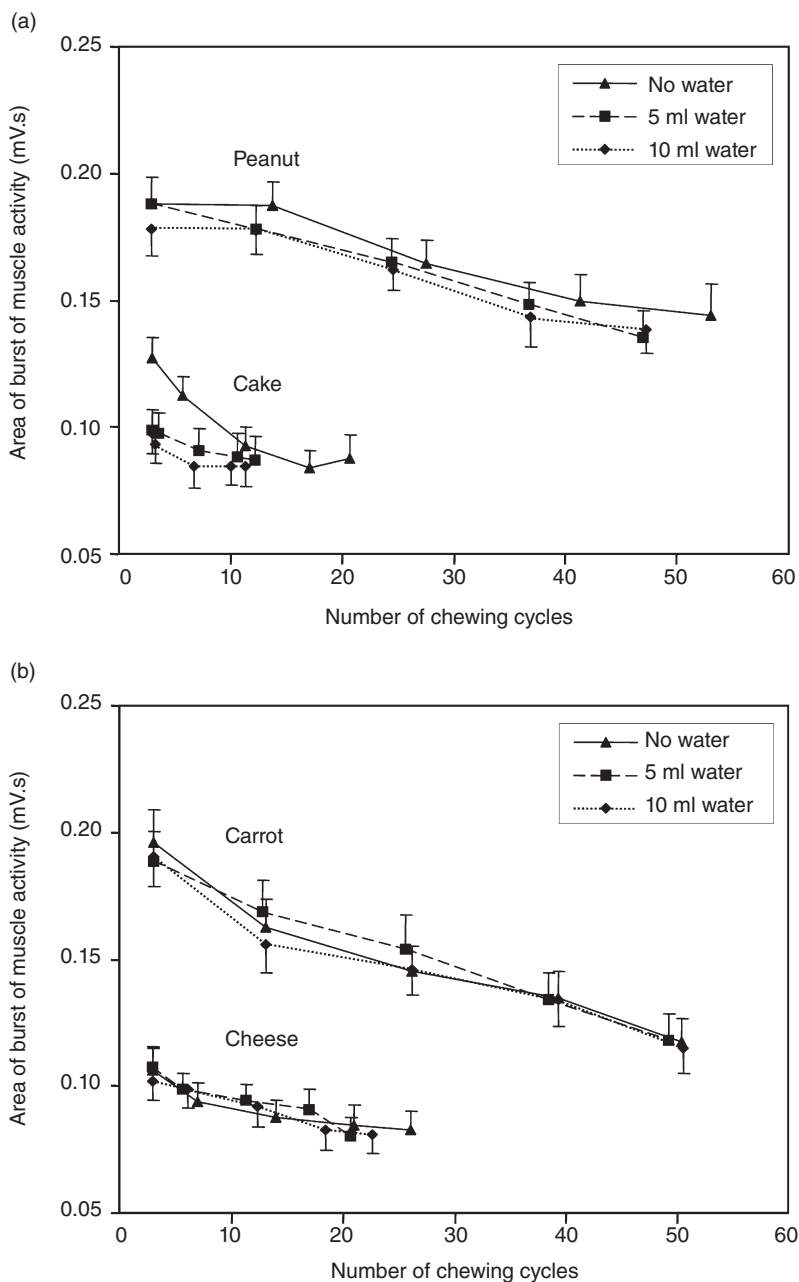


Figure 4.8 Average muscle activity per chewing cycle in five different phases of chewing (begin, 25%, 50%, 75% and end) for various food-fluid combinations. Data points along a line represent the five phases of chewing. Five foods were chewed without added water (solid lines), with 5 ml (dashed lines) and 10 ml water (dotted lines). Reproduced from van der Bilt *et al.*, 2007, with permission from John Wiley & Sons.

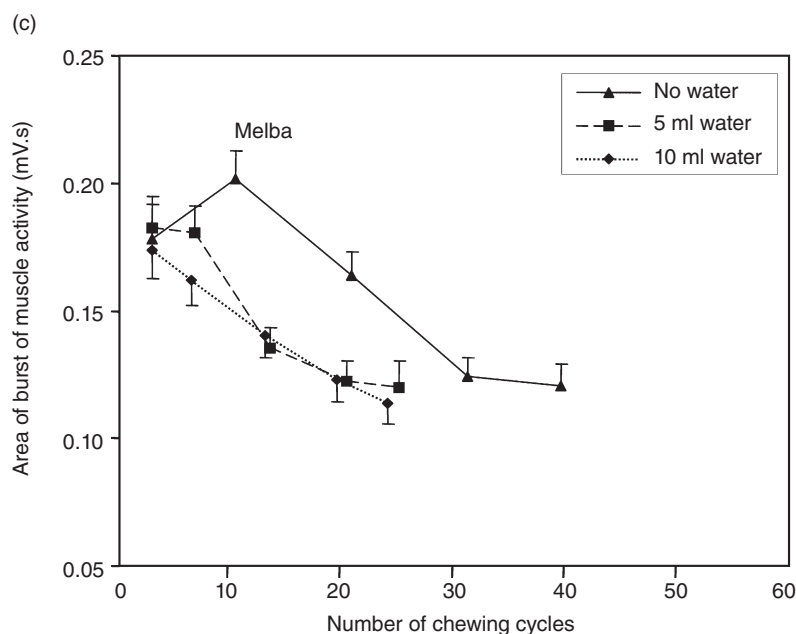


Figure 4.8 (Continued)

gherkins, mushrooms and olives). The boluses obtained from these foods contained many large particles. Harder foods needed more chewing cycles before swallowing so better particle fragmentation and bolus salivation was achieved (coconut, carrots).

The influence of texture on the chewing process has also been studied with meat. Chewing tests were performed with meat of two different textures: tough and dry versus tender and juicy meat (Mioche *et al.*, 2003). Mechanical shear force of the meat samples was determined before chewing and after chewing, when the bolus was ready to be swallowed. Texture differences between the two types of meat remained significant even when the boli were ready to swallow: the toughest meat gave the toughest bolus, despite being chewed with more strokes. Muscle activity was higher for the chewing of tough meat than of tender meat. The percentage of saliva incorporated into the bolus ready to swallow of the tough meat was significantly higher than the percentage of saliva in the bolus of the tender meat.

4.3.4 Muscle activity and jaw movement in various phases of chewing

During chewing, the food bolus or food particles are reduced in size, saliva is produced to moisten the food and flavours are released. As a result jaw muscle activity and jaw amplitude decrease while mastication proceeds as the food bolus is softened (Kohyama and Mioche, 2004; van der Bilt *et al.*, 2007). The decrease in muscle activity during the chewing process is nicely illustrated in Figure 4.8. The softening of the food is caused by structure breakdown to smaller particles (for high moisture foods such as carrot and brittle foods such as peanut), by temperature raising (for fatty foods such as cheese) and by action of the water and α -amylase of saliva (for dry foods and foods containing starch such as cake

and melba toast). Adding 5 or 10 ml water to the food had an effect on both the number of cycles until swallowing as well as the muscle activity for cake and melba toast (Figure 4.8). These are dry products requiring a sufficient amount of saliva to be added to form a coherent bolus safe for swallowing. In a study on edible elastic model foods it was shown that vertical and lateral jaw amplitudes, the duration of a chewing cycle and the muscular work steadily decreased as mastication progressed (Lassauzay *et al.*, 2000). Similar results were observed for dentate subjects who chewed meat: muscle work per chewing cycle gradually decreased during the chewing process (Yven *et al.*, 2006). The change in the pattern of jaw movement during the chewing process suggests continuous sensory modulation of the motor output to the mandibular musculature (Hiemae *et al.*, 1996). Muscle activity could thus act as a sensory clue for certain food sensory properties such as tenderness of meat (Mioche, 2004).

The following review issues/articles may be helpful in further study:

- Special issue of the *Journal of Texture Studies* on 'Mastication and food texture' (Nishinari, 2004).
- Special issue of *Physiology & Behaviour* on 'Making sense of food' (Hamer *et al.*, 2006).
- Review article on 'The neurocognitive bases of human multimodal food perception: Sensory integration' (Verhagen and Engelen, 2006).
- Review article on 'Oral physiology and texture perception of semisolids' (Engelen and van der Bilt, 2008).
- Review article on 'Food oral processing' (Chen, 2009).

4.4 NEUROMUSCULAR CONTROL OF CHEWING AND SWALLOWING

The movement of the jaw, and thus the neuromuscular control of chewing, plays an important role in the comminution of food. Chewing requires muscle activity to make the movements of the jaw and to exert forces in order to cut or grind the food. A relatively low level of muscle activity is observed in the surface EMG of the closing muscles of subjects making pseudo-chewing movements without food. More muscle activity is generated if the closing movement is counteracted by food resistance (Thexton, 1992; Ottenhoff *et al.*, 1992). Apparently, a small part of the muscle activity observed during chewing is needed just for the basic rhythmic movements of the jaw, and additional muscle activity is required to overcome the resistance of the food. The masticatory forces are controlled very precisely and these forces change from bite to bite and depend on the consistency of the food: more muscle activity is observed for harder foods (Mathevon *et al.*, 1995; Agrawal *et al.*, 1998; Mioche *et al.*, 1999; Peyron *et al.*, 2002). Jaw muscle motoneurons are activated by three sources: the cortical masticatory area, which initiates and stops mastication and delivers pre-programmed movement patterns depending on expectations and feedback, the central pattern generator (CPG), which provides basic rhythmic activity to the jaw muscles, and peripheral feedback, which modifies jaw muscle activity (Dellow and Lund, 1971; Lund, 1991). Reviews were published on: the generation of the central masticatory pattern and its modification by sensory feedback (Lund and Kolta, 2006), the adaptation of masticatory patterns to the biomechanical properties of food (Lund and Kolta, 2005), the reflex control of human jaw muscles (Türker, 2002) and the functional roles of oral reflexes in chewing and biting (van der Glas *et al.*, 2007).

4.4.1 Cortical masticatory area

Site-specific repetitive stimulation of the cortical masticatory area induces various patterns of rhythmic jaw movements in mammals (Morimoto and Kawamura, 1973; Lund *et al.*, 1984; Martin and Sessle 1993). The activity of most neurons in the masticatory cortex is higher during ingestion than during mastication, which suggests that the masticatory cortex plays a major role in setting the parameters of the first bite (Lund and Kolta, 2006). The pathways that originate from the masticatory cortex are used for the conscious initiation and termination of mastication (Türker, 2002). The masticatory cortex may also contribute to the continuous modulation of the masticatory pattern evoked by the central pattern generator. The masticatory cortex may set the effectiveness of the synaptic input to motoneurons that innervate jaw muscles or release a pre-programmed movement pattern, depending on the food resistance encountered in the previous bite (Türker, 2002).

4.4.2 Central pattern generator

Experiments on animals have established the existence of a rhythm generator for mastication which consists of a group of cells located in the brain stem, known as the central pattern generator (CPG) (Dellow and Lund, 1971; Nozaki *et al.*, 1986). The basic rhythmic activity of the jaw-opening and jaw-closing muscles is known to be generated by the CPG. Cortically evoked rhythmic trigeminal activity remained present in animals after elimination of sensory feedback from peripheral receptors (Dellow and Lund, 1971; Goodwin and Luschei, 1974). This shows that neither muscle spindle afferents nor periodontal afferents are essential to the basic rhythmic activity patterns of mastication. Cortical stimulation of an anaesthetised rabbit induced rhythmical mandibular movements in the animal (Morimoto *et al.*, 1989). The central pattern generator may be switched on by activity of higher centres or by intraoral stimuli (Thexton, 1973; Lund, 1976). The existence of the masticatory CPG in human subjects has not been directly shown but rather has been assumed from circumstantial evidence, such as the existence of the suckling reflex in infants (Finan and Barlow, 1998), phase-dependent modulation of mastication (Svensson *et al.*, 1997), phase-dependent modulation of mandibular stretch reflex sensitivity (van der Bilt *et al.*, 1997), phase-dependent modulation of exteroceptive jaw reflex (Hück *et al.*, 2004; Lobbezoo *et al.*, 2009) and the interaction among mastication, respiration and swallowing (McFarland *et al.*, 1994).

4.4.3 Peripheral feedback

Comparison of the movements and the activity patterns in the motor nerves evoked by cortical stimulation of the paralysed animal with those of natural chewing before paralysis, has demonstrated the important role of somatosensory feedback in mastication (Lund, 1991). During cortical stimulation, the central pattern generator produces stereotyped open-close cycles, whereas during natural chewing the movement trajectories of the consecutive chewing cycles vary considerably (Lund, 1991). Moreover, the activity of the jaw-closer α -motoneurons is much smaller in fictive mastication than during natural chewing. This suggests that to adequately fulfil the motor tasks of the mandible during chewing, the central nervous system requires information about the position and velocity of the mandible, about the forces acting on the mandible and on the teeth and about the length and contraction velocity of the muscles involved. An increase of the amplitude and the duration of the

activity of the jaw-closing muscles of the rabbit was observed, when cortically induced rhythmic open-close movements were obstructed by a steel ball or a foam strip between antagonistic teeth (Lavigne *et al.*, 1987; Morimoto *et al.*, 1989, 1995). This effect was reduced after elimination of feedback from the periodontal pressoreceptors by deafferentation. When spindle cell bodies were also destroyed, the facilitation of the jaw-closing muscles disappeared almost completely (Morimoto *et al.*, 1999). It was concluded that periodontal pressoreceptors and muscle spindles provide positive feedback to the jaw-closing muscles during mastication.

4.4.4 Simulated chewing experiments

The neuromuscular control of chewing in humans has been studied during simulated masticatory movements (for example Ottenhoff *et al.*, 1992; Abbink *et al.*, 1997; Naser-Ud-Dins *et al.*, 2010). In these studies food resistance was simulated by a computer controlled external load, acting on the mandible in a downward direction during closing (Figure 4.9). During the experiments, the subjects made rhythmic open-close movements at their natural chewing frequency, controlled by a metronome (Ottenhoff *et al.*, 1992). Sequences of cycles with a load were unexpectedly alternated with sequences of cycles without a load. Jaw movement, and EMG of the masseter, temporalis and digastric muscles were recorded. It was demonstrated that the additional muscle activity needed to counteract the external load consists of two components: an anticipating component starting before the onset of the food simulating load and a peripherally induced component starting after the onset of the load. The anticipating component was generated only if a counteracting load was expected. The onset of the anticipating muscle activity occurred immediately after the

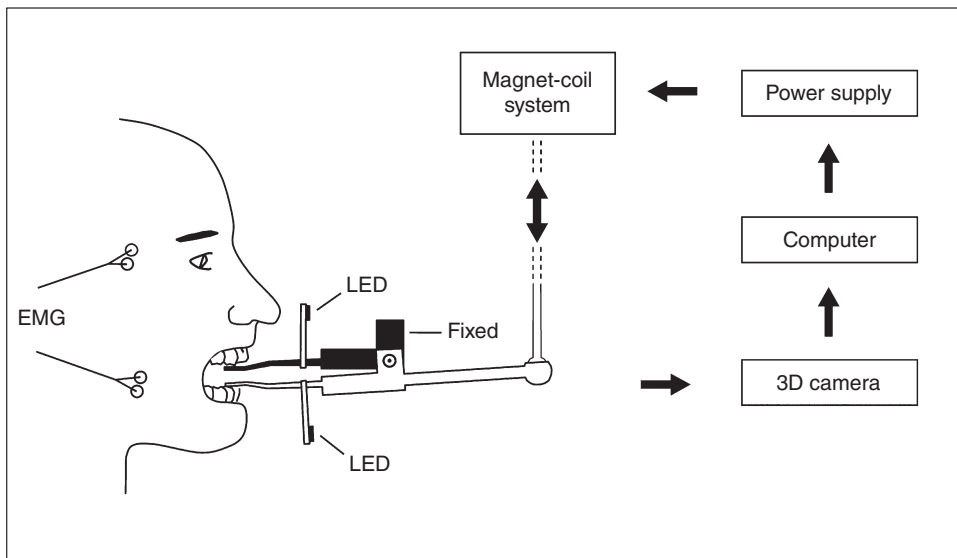


Figure 4.9 Experimental setup for external loading of jaw muscles. Reproduced from, van der Bilt *et al.*, 2006, with permission from Elsevier.

moment that the jaw started closing. Peripherally induced muscle activity was generated on average 25 ms after the onset of the load. About 85% of the muscle activity needed to overcome the external load was peripherally induced, which indicated that the muscle activity was mainly of sensory origin. However, when the movement rate of chewing was doubled (fast chewing with 120 cycles per minute), the contribution of peripherally induced muscle activity decreased to only 40%. Therefore, as jaw movement speed increased, emphasis in the control of the muscle activity shifted from sensory induced (closed-loop) to feed-forward (open-loop) control (Abbink *et al.*, 1999a). Muscles spindles are primarily responsible for the peripherally induced muscle activity as was demonstrated in an experiment on anaesthetised rabbits (Morimoto *et al.*, 1995). An experiment with rhythmic arm movements, comparable to the rhythmic jaw movements described above, showed that arm and jaw muscles responded differently to loading (Abbink *et al.*, 1999b). In the arm muscles, there was little reflex activity but a large anticipatory response, which indicates that the role of reflexes in these rhythmic arm movements was less important than the role of reflexes in rhythmic jaw movements. Furthermore, symmetrical responses were observed in biceps and triceps, which indicates similar motor control in both arm muscles. In contrast, large differences in reflex activity between masseter and digastric muscles were observed, indicating fundamental differences in sensory feedback to the jaw-closing and jaw-opening muscle (Abbink *et al.*, 1997).

The masticatory system is mainly closed-loop controlled. A reason for this may be the fact that the relatively large forces needed for food fragmentation must be controlled under uncertain conditions. First, no optical feedback is available in the chewing process. Furthermore, food resistance may vary largely from cycle to cycle. Thus, immediate muscle response is necessary to maintain a constant chewing rhythm. Furthermore, damage to the dental elements must be avoided when biting through hard and brittle food. Force-velocity properties of the jaw-closing muscles have been proposed as the principal factors responsible for halting jaw closure in the situation where the food resistance suddenly disappears (Slager *et al.*, 1997). The force of the jaw-closing muscles will decrease when they shorten, while the force of the jaw-opening muscles will increase when they are stretched. This will result in a vanishing of the chewing force (Slager *et al.*, 1997). The limitation of the chewing force by reflex mechanisms (latency of 8–9 ms between the EMG inhibitory period and the reduction of force (Türker and Jenkins, 2000)) would be too slow to limit the jaw velocity at tooth contact. The force-velocity properties of the muscles provide a quick mechanism for dealing with unexpected closing movements and so avoid damage to the dental elements (Slager *et al.*, 1997).

The muscle spindles of the jaw-closing muscles provide positive feedback to the alpha motoneurons. It is generally assumed that the feedback is modulated during chewing so that counterproductive forces of the jaw-closing muscles can be avoided during jaw opening (Lund and Olsson, 1983). Muscle spindle feedback should be suppressed during jaw opening. Indeed, jaw-jerk reflexes elicited during simulated chewing appeared to be modulated (van der Bilt *et al.*, 1997). Pronounced reflexes were observed at the onset of jaw closing, during the closing phase and at occlusion. No or only weak jaw-jerk reflexes were present during jaw-opening. The modulation of masticatory reflexes during simulated chewing has also been studied by delivering mechanical taps (1 and 2 N) to the upper left central incisor with a tooth stimulator (Naser-Ud-Dins *et al.*, 2010). The taps were delivered each time the jaw passed through the mid-gape point during jaw closing and opening. Reflexes were also elicited during a static task with the jaw at mid-gape position. Periodontal mechanoreceptor- and muscle spindle-mediated reflex components were differentiated by

performing experiments without and with periodontal anesthesia. Both periodontal mechanoreceptor and muscle spindle reflexes were reduced during simulated masticatory chewing as compared to the static condition (Naser-Ud-Dins *et al.*, 2010). Modulation of exteroceptive jaw muscle reflexes, elicited by light noxious electrical stimulation of the lower lip, has also been studied during simulated chewing (Hück *et al.*, 2004; Lobbezoo *et al.*, 2009). Reflexes in response to mildly painful stimuli were 'gated' during simulated mastication: as the teeth moved closer toward occlusion, the inhibitory response was progressively reduced. Conversely, responses to moderately painful stimuli became stronger as the teeth moved closer toward occlusion (Lobbezoo *et al.*, 2009). The modulation of jaw muscle reflexes allows smooth mastication to occur as it gates out mildly painful signals while stronger responses occur when the signal indicates potential or actual damage closer to occlusion (Lobbezoo *et al.*, 2009).

4.4.5 Neuromuscular control of chewing crispy food

The crispy/crunchy nature of food products is an important sensory characteristic on which consumers base their appreciation. When we chew crispy food, the jaw decelerates and accelerates as a result of resistance and breakage of food particles. Besides the peripheral feedback in neuromuscular control of chewing, sensory inputs also cause sensations of texture (Dan and Kohyama, 2007). The characteristic breakage behaviour of a crispy food is thus detected. It is essential for the sensory sensation. Our chewing muscles will generate the chewing force needed to break the food. The electrical activity of the chewing muscles will abruptly decrease when the food breaks, thus preventing too fast jaw closing and damage of the teeth. The breakage behaviour of a crispy food during chewing could be quantified by studying the neuromuscular control of the jaw movement during chewing of crispy foods. Such a study was recently performed on crispy foods (Hück *et al.*, 2005). The electromyogram (EMG) of the jaw closer muscles, the jaw movement and the acceleration of the jaw were measured while a subject chewed Brazil nuts, carrots and biscuits. Several distinct peaks in the acceleration of the jaw were detected in the first cycles while chewing on nuts and carrots (Figure 4.10). Furthermore, unloading reflexes in the corresponding EMG signals were observed. More, but less pronounced, peaks in the acceleration of the jaw were observed when the subject chewed biscuits.

Another approach to studying the chewing of crispy foods is to simulate the mechanical resistance of a crispy food (Hück *et al.*, 2005). In that way the breakage behaviour of a food during chewing can be manipulated in a reproducible way. Instead of the food resistance present while chewing on a food, an external load on the lower jaw was generated by a magnet-coil system (Figure 4.9). The external load thus mimics the load that would be present while chewing a crispy food. The force-deformation characteristics, as obtained from chewing a crispy food, were used to programme the load for simulated chewing. The simulated crispy food resistance should thus elicit similar muscle activity and jaw movement as with the natural food. Indeed, the muscle activity evoked while chewing on a natural food was very similar to the muscle activity observed during simulated chewing with a corresponding load profile (Figure 4.11). The skull vibrations occurred in synchronous with acceleration of the jaw, which occurs when the food breaks or after a dip in the load profile. Significant differences in texture attributes were observed for load profiles that simulated different breakage behaviour of a food. It can be concluded that simulated chewing is a promising tool for studying neuromuscular and sensory aspects of chewing crispy foods in a controlled and reproducible way.

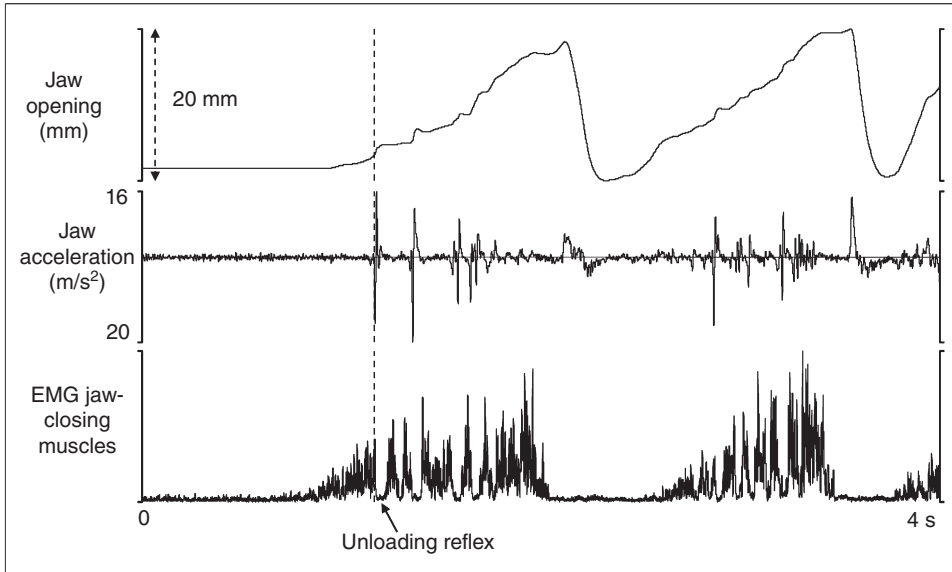


Figure 4.10 Jaw movement, jaw acceleration and rectified jaw muscle activity of a subject who starts chewing on a Brazil nut. The dashed line indicates the first breakage of the nut. The breakage is followed by an unloading reflex in the jaw closing muscles. Reproduced from van der Bilt *et al.*, 2006, with permission from Elsevier.

The following review issue may be helpful in further study:

- Special Issue of *Archives of Oral Biology* on ‘Mastication’ (Türker and Cadden, 2007).

4.5 CONCLUDING REMARKS

During chewing food is reduced in size, while saliva moistens the food and binds the masticated food into a bolus that can be easily swallowed. Characteristics of the oral system, such as the number of teeth, bite force, chewing movements and salivary flow will influence the masticatory process. Properties of the food, such as hardness, moisture and fat content will also have an influence on chewing. Numerous receptors in the mouth and nose respond to the ingested food and monitor the changes during chewing. This leads to perception of taste, odour and texture of the food.

The teeth are important in the masticatory system. They form the occlusal area where the food particles are fragmented. This fragmentation depends on the total occlusal area and thus on the number of teeth. Loss of teeth or malocclusion will lead to reduced masticatory performance. Another important factor in mastication is bite force. A higher bite force leads to better fragmentation of the food. Maximum bite force was found to be significantly lower in denture wearers than in persons with a full natural dentition. The movement of the jaw, and thus the neuromuscular control of chewing, also plays an important role in the comminution of the food. Finally, the production of sufficient saliva is indispensable for good chewing. The water in saliva moistens the food particles, whereas the sali-

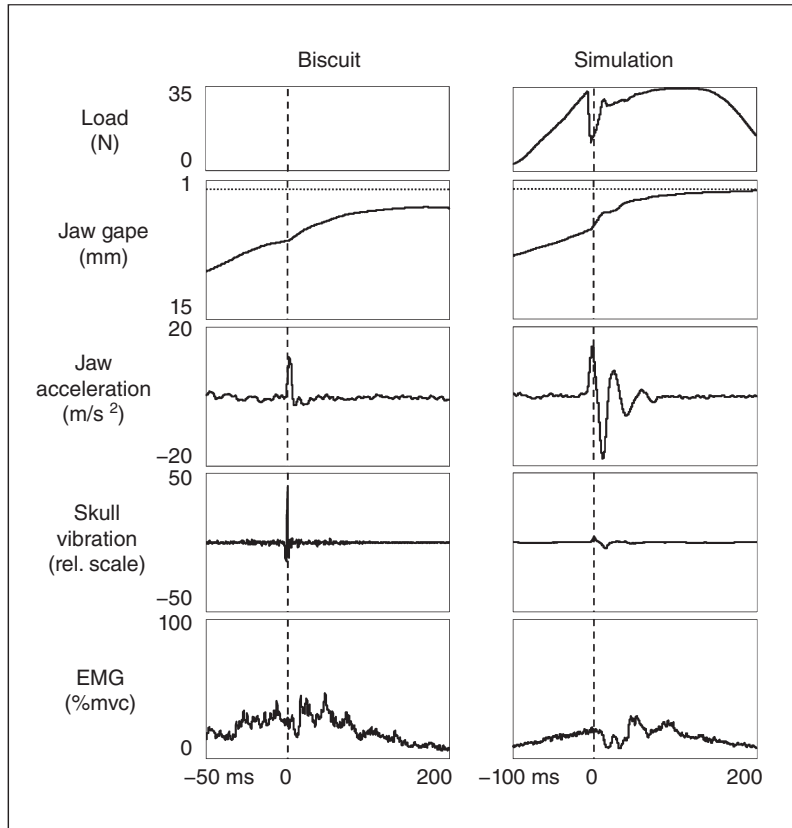


Figure 4.11 The upper row depicts the load on the lower jaw. The other rows show jaw gape, jaw acceleration, skull vibration and rectified muscle activity for chewing biscuit and simulated chewing. Reproduced from van der Bilt *et al.*, 2006, with permission from Elsevier.

vary mucins bind masticated food into a coherent and slippery bolus that can be easily swallowed.

Characteristics of the food are known to influence the masticatory process. Food hardness is sensed during mastication and affects masticatory force and mandibular jaw movements. Food characteristics have a large influence on the number of chewing cycles needed to prepare the food for swallowing. Dry and hard foods require more chewing cycles as more time is needed to break the food down and to add enough saliva to form a cohesive bolus suitable for swallowing.

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5 Breaking and Mastication of Solid Foods

Carolyn F. Ross and Clifford L. Hoye Jr.

5.1 INTRODUCTION

Food texture has been defined as all of the rheological and structural attributes of a product perceptible by mechanical, tactile, visual and auditory receptors (ISO, 1981). In order to perceive these attributes, the human senses of sight, sound and touch are employed. While auditory and visual perceptions provide useful information regarding food texture, tactile texture provides the most valuable information. Tactile texture can be divided into phase changes in the oral cavity, mouthfeel characteristic, tactile texture perceived when manipulating the product by hand and oral tactile texture (Lawless and Heymann, 1998).

The perception of oral tactile texture through oral processing involves the modification of the foods' mechanical and fracture properties, particularly important for solid foods exhibiting complex composite structures. When food is placed in the mouth, the food is destroyed by the act of mastication until it is ready to be swallowed. The purpose of mastication is to break the food into fragments small enough to swallow and lubricate the fragments with saliva. This breaking of food structure through mastication also results in an enhanced release of flavour and taste compounds (Prinz and Lucas, 1995). During mastication, specific oral processing steps occur including grip and first bite, first stage transportation, second stage transportation and bolus formation, all of which prepare the sample for swallowing.

Texture and rheology are key factors in food acceptability by individuals (Lawless and Heymann, 1998). This acceptability arises from the texture of the food itself as well as the flavour and taste compounds released during mastication. In the past, the focus of food texture and rheology studies has been to create more acceptable foods, a critically important aspect of food product development. However, the perception of texture differs, with variation observed due to physiological differences between individuals. In light of this knowledge and the interest in developing acceptable food products for an ageing population, in recent years interdisciplinary studies have been conducted to understand and solve the problems in mastication and deglutition in an aging society.

This chapter will focus on solid foods, and specifically their breaking and mastication during oral processing. The principles of mechanical properties and mechanical strength

will first be addressed in the context of the rheological nature of the food. Food oral management will then be presented, including the involvement of the tongue. Oral processing and oral selection will include a description of the breakage function of solids foods and food particle crack initiation and propagation, as well as the correlations between food breakage function and mechanical properties.

5.2 MECHANICAL PROPERTIES AND FOOD TEXTURE

Food texture may be divided into two components: first, perceived texture via human senses and second, rheology. Perceived texture includes attributes such as mouthfeel, hardness, chewiness, gumminess and adhesiveness. The second component of food texture, rheology, is the study of deformation and flow of matter (Rao, 2005). Encompassing both rheological behaviour and the perceived texture are the mechanical properties of foods. The mechanical properties form the basis for the food's sensory properties as related to texture, or the properties involved with the materials' resistance to mastication.

Texture is considered as the physical characteristics which arise from the microstructure of the food as sensed by the feeling of touch. These characteristics are related to deformation, disintegration and flow of the food under force and can be measured by the functions of mass, time and length (Bourne, 2005). This definition indicates that texture is rooted in the food structure and the reaction of this structure to applied forces. Szczesniak (1998) also defined texture as the sensory and functional manifestation of the structural and mechanical properties of foods, detected through the senses of vision, hearing, touch and kinesthetics.

An examination of the vocabulary employed by consumers to describe their perception of texture indicates the importance of mechanical attributes of foods on the characterisation of texture. Mechanical characteristics are described in terms of hardness, cohesiveness (brittleness, chewiness, gumminess), viscosity, springiness (plastic or elastic) and adhesiveness (sticky, gooey) (Bourne, 2005). In addition to considering the mechanical properties of the original food structure, all of the subsequently perceived food fragments must be measured – the perceived texture results from the sum of all of these attributes (Bourne, 2005). Hutchings and Lillford (1988) also concluded that consumers perceived texture as the total sequence of structural breakdown throughout the entire mastication process.

5.3 CHARACTERISATION OF MECHANICAL PROPERTIES

Structure–property relationships, or the connection between food structure and behaviour, are important to both materials science and food product engineering and design. In foods, structure is responsible for many of the desirable properties such as texture, appearance, and flavour and aroma release. However, unlike other engineered composites which are intended to provide physical and mechanical stability, food structures must break and fail under chewing action or risk consumer rejection.

Rheological properties are a major factor in the evaluation of food quality by the sense of touch. As defined above, rheology is defined as the study of deformation and flow of matter. This classical definition of rheology may be divided into two parts: first deformation which refers primarily to solid matter and its response to stress, and second flow which

refers to materials which are primarily fluid-like (Bourne, 2002). Foods, which often cannot be categorised as clearly liquid or solid, are often considered to be viscoelastic.

In rheological characterisation, the deformation of material is expressed in terms of the stress–strain relationship and strain rate dependency. Stress is a force measurement and refers to the outward expression of the restoring force that is developed by stretching the inter-atomic bonds that hold the material together. Strain refers to the unit change in size or shape and compares shape before and after deformation (Sahin and Sumnu, 2006). In order to better understand food rheology, stress and strain will be discussed below.

Stress is defined as the force exerted (F) divided by the cross-sectional area over which the force is acting (A):

$$\sigma = F/A \quad (5.1)$$

Normal practice is to divide by the original area (A_0) of the sample, but for large deformations, the instantaneous area (A) at any point should be used. The units of stress are Newtons per square metre (Nm^{-2}) or Pascals (Pa). Pressure is an example of normal stress (Sahin and Sumnu, 2006). Normal stress can be tensile or compressive depending on whether the stress stretches or compresses the material on which it acts. In compressive stress, a force is applied to deform the material, while in tensile stress the stress is directed away from the material. In shear stress, the force is directed tangentially to the material (Sahin and Sumnu, 2006).

Strain is the comparison of an object's shape before and after deformation. It is defined as first the ratio of the geometrical change divided by the starting dimension, second the increase in length (δl) or extension divided by the original length (l_0), known as the engineering (Cauchy) strain (e), and third the natural logarithm of the extended length divided by the original length, $\ln(l/l_0)$, known as the Hencky strain (ϵ_H). The engineering strain (e) is sufficient for most load bearing materials that operate at small strains, but strains in extensible materials cannot be adequately described by the engineering strain. Many food materials can deform to very large strains, in excess of 100%, and thus the Hencky strain (ϵ_H) is a more suitable definition of strain for food materials (Tabilo-Munizaga *et al.*, 2005).

Shear strain (γ) is defined as the angle moved in response to a shear stress (τ), defined as the ratio of the moved distance (w) of the shear plane to the thickness of the moving layer (l):

$$\gamma = w/l = \tan \theta \quad (5.2)$$

Ultimate strain, the final breaking point of a material, is an important characteristic in biological materials as many of these materials can extend to strains greater than 100%. Measurements of strains can be very difficult in soft or highly extensible materials because strain in these materials tends to be non-uniform (Sahin and Sumnu, 2006).

Foods are strain-rate dependent and solid foods may be classified as elastic or plastic based on their rheological behaviour upon mastication. In most materials, the stress–strain relationship remains linear only at small strains. When small deformations are exerted under compression, foods can show a straight line in the stress–strain plot. Young's modulus of elasticity is the ratio of stress to strain when an elastic solid material is compressed or extended, providing a measure of stiffness.

At some point the stress–strain curve deviates from linearity, and this point is defined as the yield point (σ_y). For many materials under low or moderate strain, stress is proportional to strain as described by Hooke's Law. A Hookean solid is one that displays elastic

behaviour in that when a stress is applied, the solid will deform finitely but then return to its original position after the stress is removed. Hookean solids include dry pasta, egg shells and hard candies when subjected to small strains (Steffe, 1996). At strains beyond the yield point, the material deforms plastically and on the removal of the force the material does not return to its original configuration but stays deformed permanently. Solid plastics are defined as those that do not recover their initial shape once an applied force has stopped. Elastoplastic solids exhibit intermediate behaviour, and under little stress they behave as solids, but once a critical stress is reached, they will not recover their original shape (Barbosa-Canovas *et al.*, 2005). Regardless of the behaviour displayed by the food, the rheological nature of the solid food has a significant impact on its corresponding oral management. During mastication, rheological properties are sensed in the mouth. Once the mastication process commences, foods do not generally maintain their structure. Under an applied load, such as observed during the first bite of mastication, foods undergo deformation, with changes in the flow properties of the bolus as the mass of chewed food mixes with saliva (Bourne, 2002).

Different methods have been developed to measure rheological properties. These rheological tests can be classified into two categories: direct and indirect. Direct measurements include fundamental, empirical and imitative measurements (Borwanker, 1992). Fundamental tests measure well-defined rheological properties. These tests were developed by engineers and scientists interested in describing material constructions, thus they may be of more limited usefulness when describing changes during mastication. Fundamental tests generally assume small strains (1–3%), continuous material that exhibits the same physical properties in every direction and uniform test piece. In fluids and viscoelastic materials, these measurements include steady shear and dynamic viscometric measurements. In solids, fundamental measurements include small deformation testing. Imitative techniques, while less common, imitate the conditions to which the food is subjected in practice, including mastication. An example of this technique is the instrumental texture profile method developed at General Foods, which imitates the first two bites of the mastication process with an instrument (Friedman *et al.*, 1963). Other examples of imitative methods are the Farinograph, which mimics the handling and working of bread dough, and the Bostwich Consistometer, which relates the consistency of the product to its flow in a given time (Bourne, 2002).

Empirical measurements measure parameters that may be poorly defined but through practice have been related to textural quality. These tests are rapid, easy to perform and use less expensive equipment. However, these methods often have a poor definition of what is being measured, may lack an absolute standard and may not be useful across a wide range of commodities (Bourne, 2002). They also provide an incomplete characterisation of texture. The most common texture measuring instruments making empirical measurements are those that measure force.

Force measuring instruments measure parameters such as puncture, compression-extrusion, cutting-shear, compression, tensile, torsion, bending and snapping and deformation. The puncture test measures the force required to push a probe into a food. Instruments that make such measurements include the single-probe Magness–Taylor (fruit) and the multiple-probe Armour Tenderometer. In compression-extrusion tests, force is applied to a food until its structure is disrupted and it flows through holes in the test cell. The maximum force that is applied provides a measure of textural quality. This test is used on viscous liquids, gels, fats and fruits and vegetables. Instruments that provide this measurement include the Ottawa Texture Measuring System and the Kramer Shear Press. In the cutting

shear test, the force required to cut through a product is measured. The best-known apparatus for this measurement is the Warner–Bratzler Shear, used to measure meat texture. To measure compression, tests may be either uniaxial (sample is compressed in one direction, unrestricted in the other two directions) or bulk compression (sample is compressed in three dimensions). Tensile tests assume that the food fractures in a plane that is approximately perpendicular to the plane of applied tension; the maximum force is the tensile strength of the material. Examples of instruments that measure tensile strength include Instron, Food Technology Texture Test System, or the TA.XT2 Texture Analyzer. In a torsion test, a force is applied that rotates one part of the food around an axis and the force applied is measured. An example of an instrument that uses this principle is the rotary viscometer. The bending/snapping tests are applied to foods that are in the shape of a bar or sheet. The Bailey Shortometer is used in the baking industry to measure the shortness and snapping properties of crackers and cookies and the Struc-O-Graph manufactured by the Brabender Company measures snapping and bending. All of these instrumental measures are discussed in greater detail in Bourne (2002).

5.4 ORAL SELECTION OF FOOD PARTICLES

Food oral management follows the entire process of preparing the food for swallowing, from the first bite to the final swallowing of the food. During oral processing, a series of well-coordinated decisions are made regarding oral operations and management. The tongue plays a key role in this processing.

Oral selection is a critical oral operation in the processing of solid foods. Its purpose is to ensure that large particles are selected for further size reduction while particles small enough for bolus formation are moved to the back of the oral cavity (Chen, 2009). To describe the sequence of events during oral processing, a simple model was developed by Lucas *et al.* (2002). Using this model, solid food entering the mouth is first gripped in order to fracture the food, resulting in a crack in the food and size reduction. During size reduction, decisions are made regarding whether to continue chewing or to transport the food particles for swallowing. Hiiemae (2004) further described specific steps of size reduction. In stage I transportation, food is transported from the first bite via the front teeth to the side teeth or molars. During this stage, the food is reduced in size and the textural properties of the food, as well as flavour and taste, are sensed. During stage II transportation, the size-reduced food is transported from the molar teeth to the back of the oral cavity for bolus formation.

Size reduction during mastication involves two separate processes (Epstein, 1947). The selection function describes the chance of a particle being contacted by the teeth while the breakage function describes the degree of size reduction produced by the teeth when a selected particle breaks. The breakage function relates to the specific rheological properties of the food and is discussed in the following sections.

5.4.1 The role of the tongue

The tongue plays an important role throughout the entire process of food oral management. The tongue works as a major sensory organ to sense temperature, to perceive taste and texture and as well as flavour. Most importantly, the tongue functions as a mechanical device for food manipulation and discrimination (Heath, 2002).

In order to properly sense and manage the bolus throughout the eating cycle, the tongue must change position and shape continuously. Gisell (1988) suggested that the tongue begins its positioning and movement well before the food is ingested. In a subsequent research, Okada *et al.* (2007) utilised videofluorography technique to assess tongue movement during food intake. The authors reported that the tongue moved forwards and backwards when introducing the food to the mouth, compressed the food against the hard palate, and then transported the food to the surface of the molar teeth. The authors concluded that tongue manipulation played a vital role in recognising and evaluating the volume of the bite, and that the tongue's compression of food had a role in the recognition of food texture. Chewed food particles of the appropriate size are pushed by the tongue to the back of the oral cavity for bolus formation and subsequent swallowing (Mioche *et al.*, 2002; Okada *et al.*, 2007), while larger particles are selected for further size reduction.

Rapid movements of the front of the tongue through small intrinsic muscles allow food to be repositioned during oral processing. Studies on the tongue showed its importance in aligning the food for effective mastication. Prinz and Lucas (2000) illustrated that the tongue is highly specialised and has an advanced capability of positioning and aligning food. Using wax wafers, these researchers reported that for foods possessing a longer axis, the tongue consistently positioned the wafer so that the longer axis was in line with the teeth. The alignment may have been reorganised for oral comfort or for a more efficient breakage function of the food. The tongue also participates in two other operations which allow the manipulation of the food in mouth – rolling and folding (Prinz and Heath, 2000). Tongue rolling serves to rotate the food about its long axis for optimal fragmentation while folding works to fold the food along its long axis mostly in unison with the teeth. Using ultrasonic techniques, Imai *et al.* (1995) monitored the tongue's vertical movement during the mastication of different foods. The researchers found that the tongue turned the food, mixed it with saliva, sorted out particles for bolus formation and further chewing, and aided in bolus formation. Tongue movement is dependent upon the textural nature and mechanical strength of the food being consumed. When transportation was more important than mastication, such as observed in soft foods, the anterior-posterior tongue movements were critical (Thexton, 1992).

Mastication is defined as the process of chewing, grinding or crushing with the teeth in preparation for swallowing and digestion (Bourne, 1982). It is a complex process that occurs as the food is chewed and brought into a condition that is ready to be swallowed. Mastication varies between individuals and between foods. Mastication serves many functions, including breaking the food into smaller pieces in preparation for swallowing and mixing the food with saliva. Saliva has been shown to interact with food components, resulting in structure formation or structure breakdown. One study showed that following a short time of oral processing, suggesting the involvement of saliva, 50% of bread and 25% of pasta starch was transformed into smaller particles (Hoebler *et al.*, 1998, 2000). Mastication also allows taste and odour release and increases the surface area of the food available to digestion, thus promoting easy digestion.

5.4.2 Selection function

The selection function (S) model developed by van der Glas *et al.* (1987) describes the likelihood of a particle being contacted by the teeth. For a given mouthful of food particles, the selection function exhibited a power relationship with the food particle size: $S(x) = f(x^2)$ (Figure 5.1). To determine this relationship, different sized food particles were used to monitor size reduction during the mastication process. The proportion of these particles

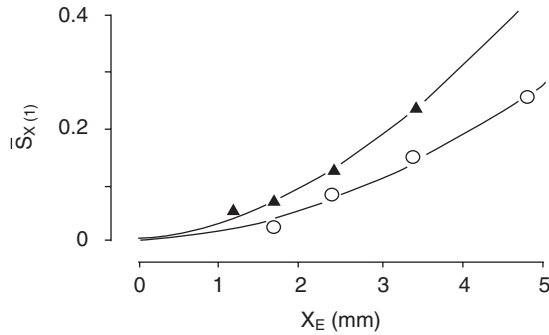


Figure 5.1 The selection chance per chew ($Sx(1)$) of two food mixtures A ($\circ$) and B ($\blacktriangle$). X_E (mm) represents the edge size of the food particle. The curves were generated by fitting pooled data for each particle size. From van der Glas *et al.*, *Journal of Dental Research* (vol. 66 Issue 10), copyright 1987 by Sage Publications. Reprinted by permission of SAGE publications.

that was broken during each chew and the selection function were determined as described above (van der Glas *et al.*, 1987). Although a larger particle was much more likely to be selected for size reduction as predicted by the power model, it appears that the degree of fragmentation reached a maximum at a particle size of about 4 mm (Chen, 2009). The selection function is also dependent on the likelihood of food particles clumping together to form a bolus as they are mixed with saliva (Lucas *et al.*, 2002).

The above model proposed by Lucas *et al.* (2002) is generally accepted because of its simplicity, but whether it is applicable to oral processing is under question. Points of concern regarding the model include: firstly, that the model interprets food particle selection as random selection, which in reality is not the case, and secondly, that the model does not explain the effect of shape of the particle on oral selection.

5.5 BREAKAGE FUNCTION

5.5.1 Definition of breakage function

In contrast to the selection function, the breakage function is an easily measurable parameter representing the oral performance in breaking up a food product and is highly dependent upon the mechanical properties of the food. Breakage function yields a quantitative characterisation of size reduction produced by teeth when a selected particle breaks, and this function bridges the gap between rheological properties of a food and its sensory performance.

Breakage function is defined as the fragment distribution of broken particles formed per chew compared to the size of the parent particle (Lucas *et al.*, 2002). Defined further, if the parent particles have a small and finite size range x to $x + \delta x$, then the particle distribution has its reference built up in various sizes y , where $y \leq x$. Figure 5.2 shows this relationship for a value of y which was determined by sieving the fragments produced per chew through a mesh size equal to half the parent particle. The measured percentage of the fragments which have passed through the screen is taken as the breakage function $B_{(0.5)}$. Figure 5.3 also illustrates the breakage function. For any initial particle size, the breakage function $B(x)$ can be described by:

$$B(x) = 1 - (1 + r \cdot x/x_0)(1 - x/x_0)^r \quad (5.3)$$

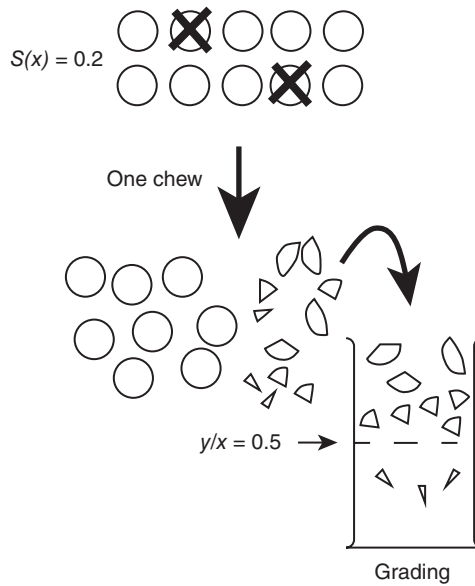


Figure 5.2 The breakage function as shown by the reduction in size of the parent particle to fragments of broken particles. From *Food Quality and Preference* **13**:4, Lucas *et al.*, 2002, 'Food physics and oral physiology', with permission from Elsevier.

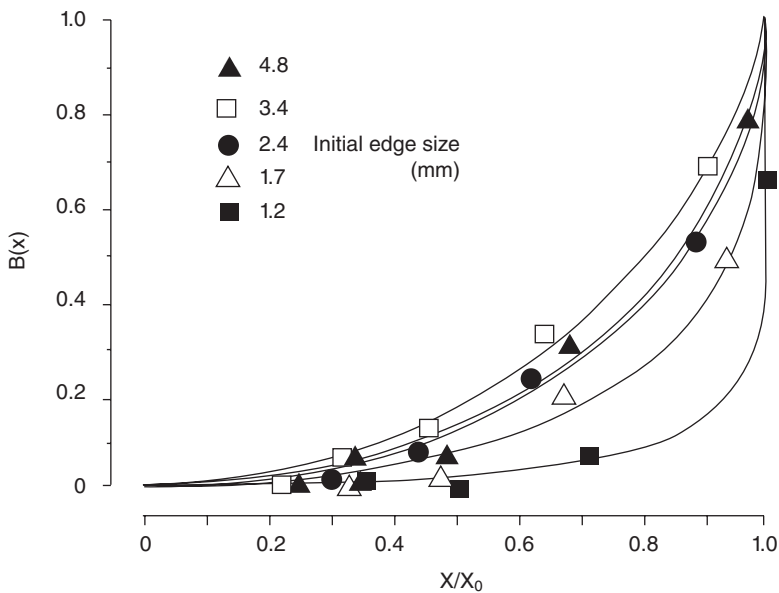


Figure 5.3 The influence of initial particle size on breakage function $B(x)$. $B(x)$ is defined as the weight fraction of selected particles with initial size x_0 which break down to particles smaller than sieve size (x) . From van der Glas *et al.*, *Journal of Dental Research* (vol. 66 Issue 10), copyright 1987 by Sage Publications. Reprinted by permission of SAGE publications.

where $B(x)$ is the weight fraction of selected particles, x_0 are the particles at their initial size, x are the particles smaller than sieve size and r is related to the degree of fragmentation. Larger r values correspond to a higher degree of fragmentation. If using a criterion x equivalent to half x_0 , then the above equation can be derived as

$$B(0.5) = 1 - (1 + r/2)(1/2)^r \quad (5.4)$$

In order to determine the breakage function, subjects were given a single piece of food to chew sealed inside a finger cot (thin latex bag) in order to avoid the interference of saliva. Subjects placed the finger cot in their mouths, and made one bite using their post-canine teeth. The bag was then expectorated, opened, and subjected to image analysis in order to determine the number and/or the total surface area of fractured particles after one chew (Al-Ali *et al.*, 1999). The percentage of the particles that passed through the mesh screen represented the breakage function value (van der Bilt *et al.*, 1993; Mowlana and Health, 1993).

The breakage function can also be expressed as area/volume ratio increase after the breaking action:

$$(A_1/V)^{0.5} - (A_0/V)^{0.5} \quad (5.5)$$

where A_0 represents the area of the particles prior to ingestion, A_1 represents the fractured surface area after the chew, and V represents the volume of the particle. This formula, based on research by Bond (1952), was consistent with the principles of fracture mechanics and dependent on the reciprocal of the square root of particle size.

5.5.2 Crack initiation and propagation

The response of a solid food to loading force is a function of the geometry and the mechanical properties of that food. During mastication, although the exact loading mechanisms changes with each chew, a simple geometry must be assumed initially to find the food property group that describes the deformation and cracking response (Lucas *et al.*, 2002).

Three basic assumptions about breakage function during mastication may be made (Lucas *et al.*, 2002; Agrawal *et al.*, 1997). In the first assumption, food particles are loaded in the closing phase of jaw movement, and the space in which the particle can break up is small and will ultimately limit fragmentation. In the second assumption, the cusps of the premolar and molar teeth, because they physically protrude from the working surface of the teeth, are more likely to form the critical contacting points with the food particle compared to the ridges of the teeth. The third assumption is that particle fragmentation during loading in food particles follows the storage of elastic strain energy, the release of which causes the growth of cracks (Atkins and Mai, 1979).

A crack in a food particle may either start remotely from the cusps through bending on a three or more point cuspal support (Figure 5.4) or adjacent to the cusp tip as the particle is indented (Figure 5.5). Figure 5.4a shows the geometry for the three-point bending of a beam-like food particle. The stress application and deflection would depend on the sample geometry and the mechanical strength of the sample. If E is Young's modulus of the food, then the deflection shown in Figure 5.4b is:

$$\delta = 3Fl^3/4Ebt^3 \quad (5.6)$$

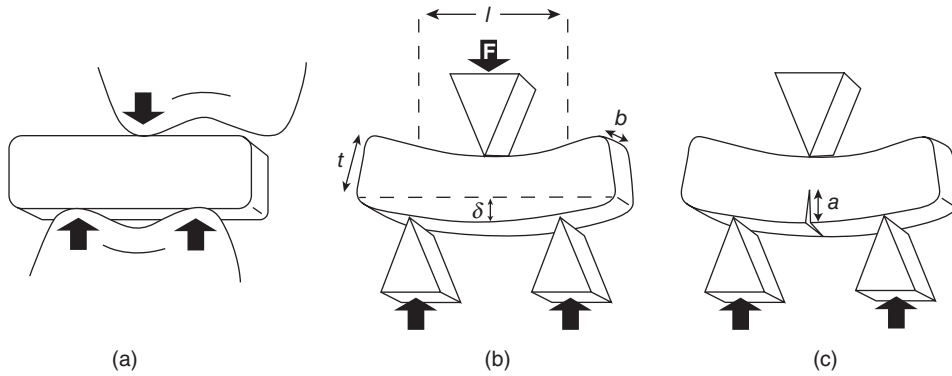


Figure 5.4 Loading of a food particle supported by the cusps of the premolars or molars: (a) before loading, (b) bending like a beam to a displacement δ and (c), after cracking. The vertical force F , span l , breadth b , and thickness t . Modified from *Food Quality and Preference* **13**:4, Lucas *et al.*, 2002, 'Food physics and oral physiology', with permission from Elsevier.

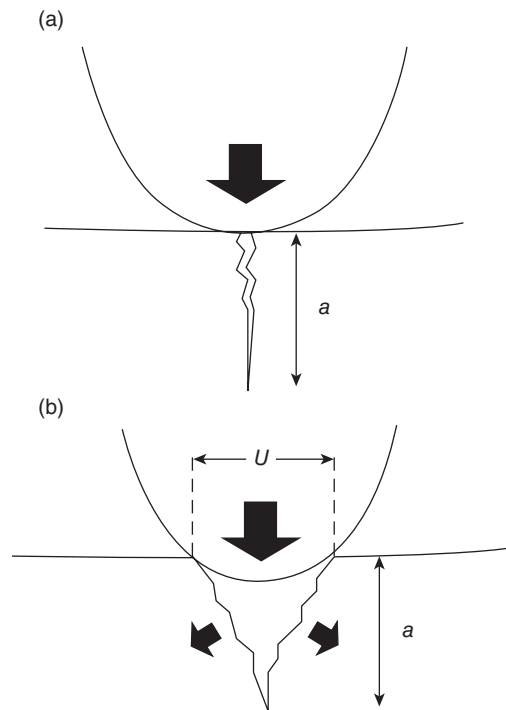


Figure 5.5 Cracking under a tooth cusp. (a) Rapid crack propagation. The crack of depth a , is growing in response to the indenting force. (b) An arrested crack pushed by wedging of the tooth in the food. The cusp has two contacts with the crack faces separated by distance u . From *Food Quality and Preference* **13**:4, Lucas *et al.*, 2002, 'Food physics and oral physiology', with permission from Elsevier.

The maximum stress, σ_F (called the modulus of rupture) is located halfway between the cuspal supports on the tension side and is defined as:

$$\sigma_F = 3Fl/2Ebt^2 \quad (5.7)$$

For failure in the food to the point of crack initiation, the combination of properties that determines the response of the food is described by the modulus of rupture divided by Young's modulus (σ_F/E). However, in food, both crack initiation and the resistance to crack propagation are important as both of these factors influence the formation of completely separated fragments. Once cracked the stress field in Figure 5.4c is given by:

$$K_{IC} = c\sigma_F(\pi a)^{0.5} \quad (5.8)$$

where c is a geometrical factor. Taking this value, dividing by E and exchanging K_{IC} for $(ER)^{0.5}$, where R is the energy dissipated in crack propagation, the following equation is obtained:

$$(R/E)^{0.5} = (\sigma_F/E)c(\pi a)^{0.5} \quad (5.9)$$

However, if cracking of the food particle begins at the cusp tip of the tooth and runs straight through the food (Figure 5.5a) then (Marshall and Lawn, 1986):

$$(ER)^{0.5} = 1.33\sigma_F(\pi a)^{0.5} \quad (5.10)$$

If cracks are formed during indentation prior to fragmentation, then an arrested crack can only continue by the displacement of the cusp into the food particle. In this situation, the cusp of the tooth acts as a wedge to pry the particle open (Figure 5.5b). The displacement criterion is defined as:

$$(R/E)^{0.5} = 0.866uw^{1.5}/a^2(1+0.64w/a^2) \quad (5.11)$$

where $w = 0.5b$ and u is the contact width of the cusp at the point where a crack of length a begins to propagate (Hoaglund *et al.*, 1972).

5.5.3 Correlations between breakage function and food mechanical properties

Two critical factors determine the breakage function of foods: first the rheological properties of the food and second the dental performance of the subject. Foods with a high breakage function result in less chewing and ultimately an easier mastication experience, whereas foods with a lower breakage function require more chewing.

The critical influence of food rheological properties on the breakage function has been demonstrated by Agrawal *et al.* (1997) who evaluated the fragmentation of 28 foods from three different categories (cheeses, raw vegetables and nuts). Linear relationships were observed between breakage function (denoted by the change in the square root of the specific surface of the particles divided by the parent particle volume) and mechanical properties. The breakage function was either linearly correlated with the square root of the product of food toughness (R) and Young's modulus ($\sqrt{R \times E}$) or inverse

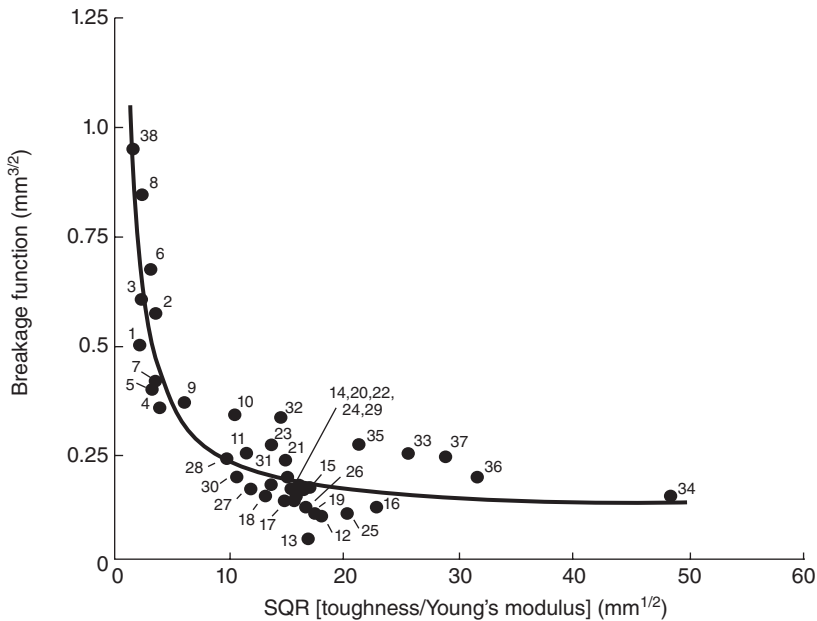


Figure 5.6 The relationship between the breakage function and mechanical properties of various foods. From *Food Quality and Preference* 13:4, Lucas *et al.*, 2002, 'Food physics and oral physiology', with permission from Elsevier.

linearly related to the square root of food toughness divided by the square root of Young's modulus ($\sqrt{R/\sqrt{E}}$).

To further delineate the relationship between breakage function and material properties in different foods, additional food items were included in the data set. Food types (38) from five different categories were added, including cheeses, raw vegetables, nuts, breads and miscellaneous (Lucas *et al.*, 2002). A master curve was created for the correlation between breakage function and material properties $\sqrt{R/\sqrt{E}}$ (Figure 5.6). Some particularly hard and brittle foods (i.e. sugar crystals and nuts) had the highest breakage function (above $0.5 \text{ mm}^{-1/2}$) but exhibited minimal values of $\sqrt{R/\sqrt{E}}$ (below $5 \text{ mm}^{1/2}$). Thus, a small change in mechanical properties (either toughness or elasticity) could lead to a significant difference in the fracture behaviour of the food (Chen, 2009). Raw fruits and vegetables exhibited reasonably high $\sqrt{R/\sqrt{E}}$ (between 5 and $20 \text{ mm}^{1/2}$) with a moderate breakage function. Softer foods including breads, cheeses, cakes and soybean curd showed the highest $\sqrt{R/\sqrt{E}}$ (up to $50 \text{ mm}^{1/2}$) but the smallest breakage function. The measurement of breakage function seemed to perform well as an indication of oral performance of hard brittle foods, but has very limited use in assessing the textural properties of soft deformable foods (Chen, 2009).

Oral fragmentation may also be dependent on the geometry of foods (Lucas *et al.*, 2002). For foods in thin sheets, toughness (R) is the determining criterion while for thick block foods, the criterion is the square root of the toughness divided by the square root of Young's modulus $\sqrt{R/\sqrt{E}}$. For foods with a high fracture force, the criterion is the square root of the toughness and Young's modulus ($\sqrt{R \times E}$). Both Young's modulus (E) and toughness

(R) are commonly referred rheological parameters of a material and can be easily determined from a standard rheological testing.

5.5.4 Limitations of breakage function

Many of the limitations associated with the breakage function are related to those factors not included in its determination. Mastication of food involves a complex series of manipulations by which both physical and chemical properties change due to interactions with saliva and the oral mucosa. Interaction with saliva results in mechanical and enzymatic breakdown, dilution and equilibration to mouth temperature (Janssen, 2007). However, saliva was not considered in the determination of the breakage function. Studies have indicated the key involvement of saliva in foods with an open structure and low moisture content such as biscuits and crackers. Pereira *et al.* (2006) studied the effect of addition of varying amounts of tap water on texture perception of melba toast, breakfast cake, carrot, peanut and gouda cheese. Results showed that added fluid affected both the physiology (number of chewing cycles and muscle activity) and the sensory perception of both texture and sound attributes. The researchers postulated that adding fluid facilitated the chewing of dry foods but did not influence the chewing of fatty (cheese) and wet products (carrot). The addition of α -amylase (Pereira *et al.*, 2006) or mucins (van der Bilt *et al.*, 2007) to the system showed no significant effect on the mastication process.

Enzyme function was also not included in the proposed breakage function. Both mechanical and enzymatic breakdown have been shown to play a role in texture perception (Janssen *et al.*, 2007). Enzymatic breakdown was found to be the dominant mechanism in the perception of fattiness, roughness and stickiness of custards (Janssen *et al.*, 2007). Most studies of enzymatic interaction with food components are conducted with starchy foods and salivary amylase played a significant role in the sensory perception of those foods (Hoebler *et al.* 1998, 2000). Thus, if at all possible a saliva–food interaction should be incorporated into the measurement of breakage function.

The dental performance of the subject is also a critical factor in the determination of breakage function. Karkazis (2002) showed that denture wearers had more regular chewing patterns, indicating less adaptation to the changes in the food structure, and had to apply higher muscle activity to produce the same chewing function as natural dentate persons. Yven *et al.* (2006) found that the chewing pattern of denture wearers was significantly impacted and lacked the adaptation to structure changes during bolus formation. They also found that in general denture wearers swallowed less fragmented boluses than non denture wearers. Woda *et al.* (2006) attributed the impaired mastication function to neuromotor deficiencies, a lack of sensitivity, in denture wearers.

5.6 CONCLUDING REMARKS

Breaking and mastication of solid foods are complex processes that require knowledge of the mechanical properties of the food, as well as food rheology. While the breakage function has been used to describe the fragmentation of food in preparation for swallowing, this function does not consider other physiological aspects, including saliva and enzyme presence, as well as dental performance. In order to fully describe the changes that are observed during mastication of solid food, these parameters should be considered in future studies.

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6 Oral Behaviour of Food Emulsions

Anwasha Sarkar and Harjinder Singh

6.1 INTRODUCTION

Dietary lipids, fats (if they are solid) and oils (if they are liquid), derived from plant and animal sources, have many critical functions in the body, such as providing essential fatty acids, acting as carriers of fat-soluble vitamins (vitamins A, D, E and K) and providing a concentrated source of energy (Kritchhevsky, 2002; Singh *et al.*, 2009). Although lipids are essential components of daily foods, their overconsumption can lead to serious medical conditions. Recent concerns about obesity, atherosclerosis and other food-linked diseases have raised considerable challenges to the food industry to produce healthy foods with a reduced amount of fat, cholesterol, salt and carbohydrate but without sacrificing their organoleptic properties (Le Révérend *et al.*, 2010; McClements *et al.*, 2009; Singh *et al.*, 2009). The consumption of low fat foods has become more than just a trend; it has become a response to public health concerns and initiatives. Over the past few decades, reduced-fat foods and fat substitutes have increasingly become a part of food business as a result of consumer demand. Unfortunately, not all these new products survive in the competitive marketplace. This is because many, if not most, of the low fat foods cannot meet the consumer's sensorial expectations, as reduction in fat content adversely affects flavour release, rheological properties, creaminess, mouthfeel and texture perception (Bayarri *et al.*, 2006; Doyen *et al.*, 2001; Malone *et al.*, 2003a, 2003b).

Modern processed foods, in which fats are mostly incorporated within the food matrix in the form of emulsions (such as sauces, yoghurt, cheese, spreads, imitation creams, salad dressings, gravies, ice creams, confectionary products, chocolate, etc.), represent a significant part of a consumer's everyday diet. Emulsified lipids play a major role in determining the texture, flavour and taste profile of processed foods. They provide not only the sensory aspects, but also structural attributes to food products; for example, emulsified fats provide appropriate firmness to whipped cream or ice cream by controlled destabilisation or partial coalescence of fat crystals (Goff, 1997). Thus, reduction of fat poses a serious threat to the overall acceptance of the product.

In order to fabricate appropriate microstructures that provide health attributes without compromising on sensorial perception, understanding the conditions experienced by

emulsions in the mouth is very important. Most thin liquid emulsions typically stay from a few seconds to minutes in the mouth. Within this short period of time, liquid foods are generally subjected to a temperature change, mechanical shear, dilution and biochemical breakdown. Flavour molecules have to be released efficiently and effectively from the matrix to ensure maximum taste and odour stimuli. It is now almost certain that the sensory perception of food emulsions is largely affected by oral processing (Engelen *et al.*, 2003a, 2003b). Knowledge of the complex interactions between the emulsion droplets and the oral components such as salivary proteins might be the key to understanding the oral behaviour and sensory perception of food emulsions. For example, it has recently been shown that the type of flocculation of protein-stabilised oil-in-water emulsion droplets in the presence of saliva significantly influences the fat-related sensory perception, that is creaminess and thickness (Vingerhoeds *et al.*, 2009).

The aim of this chapter is to provide readers with basic knowledge of the creation and stability of food structures (with the main focus on particular liquid oil-in-water emulsions) and then to discuss current advances in understanding of the oral destabilisation of food emulsions from a physico-chemical viewpoint and to relate these processes to sensory perception.

6.2 FOOD EMULSIONS IN GENERAL

The lipids in many, if not most, processed foods are present as emulsions (lipid droplets dispersed in a composite matrix of water, proteins, carbohydrates and other minor food components), which can be the end products in themselves or parts of a more complex food system. An emulsion is defined as an intimate dispersion of at least one immiscible liquid in another in the form of discrete droplets (diameter in the general range from 0.1 to 100 μm) (McClements, 2005; Singh *et al.*, 2009). There is an interfacial layer between the two phases, which may be occupied by surface-active agents, such as proteins, polysaccharides, phospholipids, monoacyl glycerol esters and so on. Basically, there are three types of emulsions: oil-in-water (O/W) emulsions, water-in-oil (W/O) emulsions and multiple emulsions, that is oil-in-water-in-oil (O/W/O) emulsions and water-in-oil-in-water (W/O/W) emulsions, as shown in Figure 6.1.

O/W refers to the type of dispersion in which oil is dispersed as droplets in the continuous aqueous phase (Figure 6.1a). Milk and cream are popular natural O/W emulsions, in

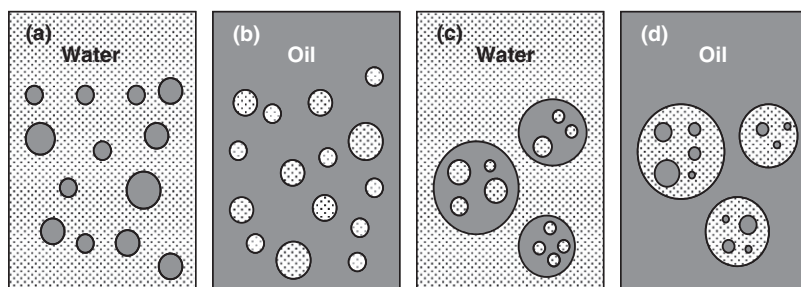


Figure 6.1 Schematic representation of emulsion systems: (a) O/W emulsion; (b) W/O emulsion; (c) W/O/W emulsion; (d) O/W/O emulsion. (The grey and dotted white areas represent oil phase and water phase respectively.)

which the milk fat globules are dispersed in an aqueous phase containing milk proteins, lactose, salts and minerals. The fat globules are stabilised by the lipoprotein membrane, which consists primarily of phospholipids. Other examples of O/W emulsions include salad dressings, mayonnaise and ice cream. In contrast, in a W/O emulsion, oil forms the continuous phase and water exists as the dispersed phase (Figure 6.1b). Butter is a common W/O emulsion, in which milk proteins, phospholipids, lactose and salts are dispersed as droplets in a continuous phase of fat cream.

Multiple emulsions refer to systems in which the dispersed phase is also an emulsion (Figures 6.1c and 6.1d). In other words, the multiple emulsion droplets themselves contain a number of internal dispersed droplets in such a way that the final dispersed phase is actually the continuous phase for the internal dispersed droplets. These multiple emulsions can be further classified as either O/W/O or W/O/W multiple emulsions. In the case of an O/W/O multiple emulsion, the internal droplets and the external continuous phase matrix are composed of oil; the internal oil droplets are separated from the external oil phase by the aqueous phase. A W/O/W multiple emulsion consists of small aqueous droplets dispersed in oil and this W/O emulsion itself is dispersed as large droplets in the continuous aqueous phase.

Generally, food emulsions are prepared using a high shear or high pressure equipment, such as colloid mills, high speed blenders and high pressure valve homogenisers, that mixes an oil phase and an aqueous phase together in the presence of a surface-active agent (McClements, 2005). The basic procedure is to force a coarse mixture of oil phase and aqueous phase through a narrow slit under the action of high pressure, resulting in cavitation, intense laminar shear flow and turbulence. At the same time, the surface-active agents, such as emulsifiers, because they are structurally amphiphilic molecules (having both hydrophobic and hydrophilic moieties), adsorb at the oil/water interface (Dickinson, 2003), creating a stabilising interfacial layer at the oil droplet surface, leading to the generation of fine uniformly dispersed droplets. In this review, O/W emulsions will be the main focus. Detailed information about emulsions can be found in a number of books (Dickinson, 1992; Dickinson and Stainsby, 1982; Friberg *et al.*, 2004; McClements, 2005).

6.3 INTERFACIAL LAYERS

In most food emulsions, the oil droplets are coated by a continuous film of adsorbed materials, such as low molecular weight emulsifiers, proteins and phospholipids, which stabilise the droplets. The structure and the composition of the adsorbed layers can be quite complicated because foods in general contain a variety of surface-active agents; all are possibly adsorbed at the interface either individually or in combination, resulting in complex multi-layered interfacial layers (Schramm, 2005), as illustrated in Figure 6.2. The nature of the interfacial layers formed depends largely on the type, concentration, charge and conformation of the adsorbed materials, and also on the kinds of interactions and competitions that occur between the adsorbed species (Dickinson, 2003; Singh *et al.*, 2009).

Generally, simple adsorbed layers are formed by low molecular weight surfactants, such as monoacyl glycerols and various fatty acid esters, that tend to orientate at the droplet surface in such a way that, during the short time scale of homogenisation, the non-polar groups strongly penetrate into the oil phase and the polar groups spread out in the bulk aqueous phase, and thus reduce the interfacial tension (Dickinson, 2003). The lower the interfacial tension, the lower the free energy of the system and, thus, there will be reduced

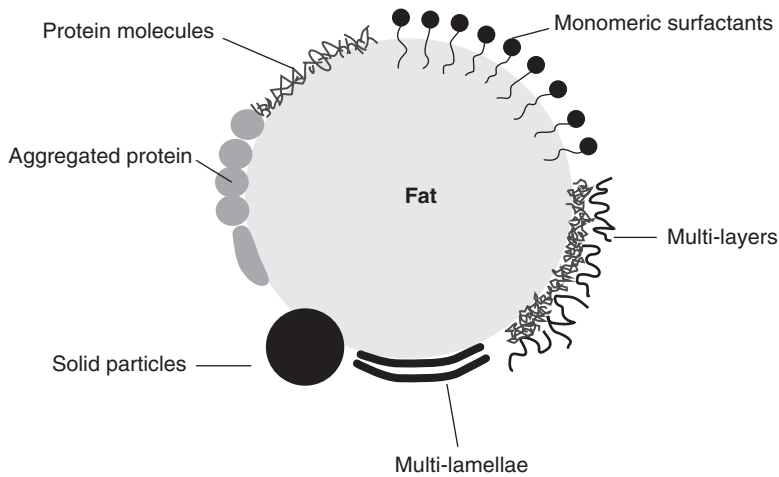


Figure 6.2 Major food-grade materials used to stabilise O/W emulsions by forming an adsorbed film at the interface. Reproduced from Singh *et al.*, 2009, pp.92–100, with permission from Elsevier.

tendency for the oil phase and the aqueous phase to form the smallest possible contact surfaces. The choice of these low molecular weight emulsifiers with optimum hydrophile–lipophile balance (HLB) allows the formation of small droplets, by forming an adsorbed layer that reduces the unfavourable contacts between the hydrophobic groups and the continuous aqueous phase (McClements, 2005; Singh *et al.*, 2009). Mixtures of different low molecular weight emulsifying agents with various HLB values can be used intelligently to provide complex adsorbed layer structures, multi-interfacial layers and liquid crystals close to the droplet surface (Friberg *et al.*, 2004).

Proteins, being an indispensable component of all processed foods, have proved to be effective functionally, providing desirable textural and other attributes to the final food products. Milk proteins such as caseins, caseinates, whey protein isolates, β -lactoglobulin and bovine serum albumins have been known for many decades as emulsifiers and a lot of work has been done on dairy-based emulsion systems, such as milk, cream, butter and ice cream. Milk proteins, in both soluble form and dispersed form, are known to be excellent emulsifiers because of their amphiphilic nature (Mulvihill and Fox, 1989). They exhibit good surface-active properties by reducing the tension at the oil/water interface and form interfacial films with different rheological properties. The role of caseins and whey proteins in stabilizing O/W emulsions has been thoroughly investigated and published (see reviews (Dickinson, 2001; Kinsella, 1984; Singh, 2005)).

When globular proteins are used as the adsorbed layers, they undergo unfolding and reorganisation of the native protein conformation to form a stabilising layer at the interface. The degree of unfolding depends largely on the flexibility of the protein molecules. As caseins have a rather flexible structure, that is they do not contain much rigid α -helix and β -pleated sheet structure (Holt and Sawyer, 1988), they adsorb rapidly at the interface, forming extended adsorbed layers up to about 10 nm thick (Dalgleish, 1990, 1995, 1996). In contrast, globular whey proteins (such as β -lactoglobulin) unfold partially, somewhere intermediate between the native state and the fully denatured conformation, resulting in

compact adsorbed layers that are only about 2 nm thick. Moreover, this partial unfolding of the whey protein structure following adsorption exposes reactive sulphhydryl groups, thus resulting in slow polymerisation of the adsorbed protein in aged interfacial layers via sulphhydryl–disulphide interchange reactions.

The sequence of surface activity reported for milk proteins is β -casein > monodispersed casein micelles > serum albumin > α -lactalbumin > α_s -casein = κ -casein > β -lactoglobulin > euglobulins (Ennis and Mulvihill, 2000). Aggregated forms of milk proteins, that is casein micelles in milk, can also adsorb to the droplet surface, although not as effectively as the molecular form of caseins (β -casein, α_s -casein) (Singh *et al.*, 2009). These aggregates generate thicker adsorbed layers, resulting in higher surface coverage. By forming charged and hydrodynamically dense adsorbed layers, these aggregated caseins contribute to the long term stability of emulsions against coalescence by both electrostatic mechanisms and steric stabilisation mechanisms respectively.

Proteins from egg white are used extensively as a functional ingredient in many processed foods because of their excellent foaming properties. It has been reported that the foaming properties of egg white proteins follow the sequence globulins > ovalbumin > ovomucoid > lysozyme > ovomucin (Johnson and Zabik, 1981). The competitive adsorption of five major egg white proteins, that is ovalbumin, ovotransferrin, ovoglobulins, ovomucoid and lysozyme, from bulk solutions having relative protein concentration ratios similar to those in egg white to the air/water interface at 0.1 M ionic strength indicated that only ovalbumin and ovoglobulins adsorbed to the interface and that the other egg white proteins were excluded from the interface (Damodaran *et al.*, 1998).

As well as animal proteins, plant proteins are used as an alternative source of food emulsifiers. Among the available plant protein sources, fractions extracted from cereals (α -gliadin from wheat) (MacRitchie and Lafandra, 1997; Örnebro *et al.*, 2000) and legumes (pea albumin, globulins from pea and soy) (Gueguen, 1989; Kinsella, 1979; Utsumi *et al.*, 1997) are preferred for food applications as they are soluble in water without the need for co-solvents (such as alcohol) (Ducel *et al.*, 2004). The interfacial properties of wheat proteins have been studied mainly at the air/water interface, particularly with reference to the coating of air cells during bread making. Keller *et al.* (1997) studied the competitive behaviour of the various gluten proteins present in wheat flour, adsorbed at the air/water interface. They reported that the sequence of surface activity of the wheat proteins was gliadin > glutenin > globulin > albumin.

Legume proteins such as pea proteins are also able to reduce the interfacial tension between the water and oil surfaces by forming a rigid membrane at the oil/water interface (Ducel *et al.*, 2004). This is due to the surface properties of their constitutive protein fractions, generally classified according to their sedimentation coefficient (S): vicilin (a trimeric 7S globulin) and legumin (a hexameric 11S globulin) (Gharsallaoui *et al.*, 2009). It has been reported that, in the case of purified pea protein in the native form, 7S globulins are more surface active than 11S globulins (Dagorn-Scaviner *et al.*, 1986). However, the surface activity of the pea globulins depends largely on pH and salt concentration because of the pH-dependent changes in its quaternary structure. For example, 11S pea legumin is a hexamer at neutral pH and high ionic strength (100 mM NaCl), but dissociates at pH 3.4 and pH 10, according to ionic strength, into a mixture of trimers, dimers and monomers (Gueguen and Barbot, 1988).

Another important leguminous protein is soy protein, which is widely used as an ingredient in food products because of its foaming and emulsifying properties (Kinsella, 1979; Peng *et al.*, 1984). It aids in emulsion formation by reducing the interfacial tension between

the water and oil, and also by helping to stabilise the emulsion by forming a physical barrier at the oil/water interface. Similarly to the storage proteins in pea, two major multi-subunit protein fractions, accounting for 70% of total soy protein, are storage globulins 7S (β -conglycinin) and 11S (glycinin), which are expected to dominate the interfacial behaviour of soy protein isolate. Dissociation and unfolding of soy globulins by physical changes (heat, pressure or alkali treatment), chemical modifications (acylation, phosphorylation or deamidation) or enzymatic methods may reduce the molecular size, improve the molecular flexibility, increase the surface hydrophobicity and thus influence the adsorption behaviour at the interface (Lakemond *et al.*, 2000; Wagner and Gueguen, 1995).

Water-soluble polysaccharides extracted from plants (starch, pectin), seaweeds (agar, carrageenan), animal sources (chitosan) and microbial sources (xanthan gum, dextran) as well as gums derived from tree exudates (gum arabic, tragacanth gum), tubers (konjac mannan), seeds (guar gum, locust bean gum) and modified biopolymers (carboxymethyl cellulose, acetylated starch) made by the chemical or enzymatic treatment of starch or cellulose are often called 'hydrocolloids' (Williams and Phillips, 2000). It is generally believed that polysaccharides stabilise emulsions by enhancing the viscosity of the continuous aqueous phase but do not adsorb at the oil/water interface unless they are contaminated with some protein residues (Dickinson, 2003). It has been shown clearly that a small amount of protein is an integral part of all gum structures (Anderson, 1986), which results in surface activity. However, claims about the interfacial activity of protein-free pure polysaccharides such as fenugreek gum also persist (Benichou *et al.*, 2002; Garti and Leser, 2001).

In an emulsion system containing both protein and polysaccharide, protein generally forms the primary interfacial layer by directly adsorbing to the oil surface. The hydrophilic polysaccharide possibly forms a thick secondary steric-stabilising layer on the outside of protein-adsorbed emulsion droplets providing the protein-polysaccharide interaction is satisfactorily attractive (Dickinson, 1994). Generally, strong electrostatic interaction between the mutually oppositely charged adsorbed protein and added polysaccharide leads to the formation of multi-layered interfacial membranes stabilizing emulsion droplets (Güzey and McClements, 2006a, 2006b). Covalent conjugates formed via Maillard reactions between proteins and polysaccharides have also attracted a lot of interest because of their higher emulsification abilities and better stabilities over wide ranges of temperature, pH and ionic strength, compared with the biopolymers alone (Shepherd *et al.*, 2000).

Phospholipids, such as lecithin derived from egg yolk or soybean, can form multi-lamellar structures or adsorbed monolayers at the interface depending on the concentration of phospholipids present during the homogenisation process (Schramm, 2005; Singh *et al.*, 2009). Proteins and phospholipids sometimes coexist at the interface and undergo complex interactions, thus modifying the stability of emulsion droplets (Fang and Dalgleish, 1993). The addition of egg yolk lecithin has also been shown to partially displace β -casein from the oil/water interface at high phospholipid-to-protein ratios (Courthaudon *et al.*, 1991a). However, phospholipids are less effective than low molecular weight surfactants, such as Tween 20; the latter have the ability to competitively displace adsorbed proteins completely from the interface (Courthaudon *et al.*, 1991b, 1991c).

Hence, interfacial layers of different structures, thicknesses, compositions and charges can be carefully designed with specific emulsifiers individually or by complex formation to meet the structural demands, environmental challenges and stability of food emulsions.

6.4 EMULSION STABILITY

The physico-chemical properties and the stabilities of emulsions are largely determined by the types and concentrations of the dispersed phase and the continuous phase, the nature of the interfacial layer, temperature, pH, viscosity and the homogenisation conditions and other processing parameters employed, such as heat treatments and enzymatic hydrolysis (McClements, 2005). The term 'emulsion stability' refers to the ability of an emulsion to resist any alteration in its properties over the time scale of observation. An emulsion is a thermodynamically unstable system, as the free energy of mixing is always positive, because of the large interfacial area between the oil and the aqueous phase. The mathematical expression for the free energy change of emulsification can be illustrated as (Hunter, 1989):

$$\Delta G_{\text{formation}} = \gamma \Delta A \quad (6.1)$$

where ΔA = change in interfacial energy and γ = interfacial tension.

The term $\gamma \Delta A$ is always positive, because the interfacial area always increases after homogenisation (McClements, 2005); therefore, the system is thermodynamically unstable and the time period for which the emulsion is stable is practically more important. An emulsion may become unstable as a result of various types of physical and chemical processes. Physical instability refers to modifications in spatial arrangement or size distribution of emulsion droplets, such as creaming, flocculation and coalescence, whereas chemical instability includes changes in the composition of the emulsion droplets themselves, such as oxidation and hydrolysis.

In the case of an emulsion, Stokes' law can explain the physical instability, particularly the creaming (that is the movement of oil droplets under gravity or applied centrifugal force to form a concentrated cream layer at the top of the emulsion without any change in the droplet size distribution), by the following mathematical expression (Hunter, 1989):

$$v_{\text{stokes}} = \frac{2r^2(\rho_1 - \rho_2)}{9\eta} \quad (6.2)$$

where v_{stokes} is the velocity of creaming, r is emulsion droplet radius, ρ_1 and ρ_2 are the densities of the continuous and dispersed phases respectively and η is the shear viscosity of the continuous phase. Hence, the kinetic stability of an emulsion can be increased or the creaming rate can be decreased by lowering the radius of the droplets, by increasing the viscosity of the continuous phase or by decreasing density difference between the two phases.

However, this law often fails to define the rate of creaming because of the simultaneous flocculation or coalescence. Flocculation has been described as a reversible aggregation mechanism that arises when droplets associate because of unbalanced inter-atomic attractive and repulsive forces (Dalgleish, 1997). In contrast, coalescence refers to a completely irreversible increase in droplet size by accretion, gradually leading to the separation of the oil phase and the aqueous phase. Commonly, two types of droplet–droplet interactions are notable, that is depletion flocculation and bridging flocculation. The mechanism of destabilisation that prevails depends on the interaction between the interfacial layer and the emulsion droplets.

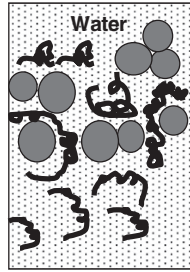


Figure 6.3 Depletion flocculation in an O/W emulsion. Particles approach because the osmotic pressure gradient pushes out the unadsorbed biopolymer. (The grey and dotted white areas represent oil phase and water phase respectively. The coil structures represent the biopolymer added to stabilise the droplets.)

6.4.1 Depletion flocculation

Generally, depletion flocculation occurs because of the presence of a non-adsorbing biopolymer in the continuous phase of the emulsion, which can promote the association of emulsion droplets by inducing an osmotic pressure gradient within the continuous phase surrounding the droplets. The mechanism of depletion flocculation is illustrated in Figure 6.3.

Basically, when the biopolymer added into the continuous phase is either unadsorbed or poorly adsorbed, the biopolymer is squeezed out of the area between two approaching emulsion droplets. The local aqueous phase concentration immediately surrounding the emulsion droplets becomes significantly lower than the overall concentration of the bulk continuous phase, resulting in an osmotic pressure imbalance. Hence, the droplets are attracted to each other, causing flocculation and leading to a loss of emulsion stability. This attraction energy can be calculated by measuring the concentration of the biopolymer and the radius of gyration of the biopolymer molecule, as shown by the following interaction potential $-w_{dep}(0)$ (McClements, 2000):

$$w_{dep}(0) = \frac{-3kT}{2} \frac{cR_v}{\rho} \left(1 + \frac{1}{2} \frac{cR_v}{\rho} \right) \left(\frac{\gamma_d}{\gamma_g} + \frac{2}{3} \right) \quad (6.3)$$

where c is the biopolymer concentration (kg/m^3), γ_d and γ_g are the radius of the emulsion droplet and the radius of gyration of the biopolymer respectively, ρ is the density of biopolymer and R_v is given by the following expression:

$$R_v = \frac{4\pi\rho N_A \gamma_g^3}{3M} \quad (6.4)$$

where N_A is the Avogadro number and M is the molecular weight of the biopolymer molecule (kg/mol).

It is suggested that most droplets are flocculated (at droplet–droplet separation distance $h = 0$) when the depletion potential ($-w_{dep}(0)$) exceeds $4 kT$ (McClements, 2000). The reversible bonds formed during this depletion flocculation are generally weak and flexible.

Dickinson *et al.* (1997) investigated O/W emulsions (35.0 or 45.0 vol% oil) using sodium caseinate as the sole emulsifying agent. They showed that, at a protein content of nearly 2.0 wt%, the emulsion droplets were protected from flocculation by a steric-stabilizing layer of casein molecules. The emulsion was stable against flocculation, coalescence and creaming for several weeks. However, when the protein content was increased to above 3.0 wt%, the presence of unadsorbed caseinate in the continuous phase gave rise to depletion flocculation, resulting in serum separation. This was considered to be due to the presence of small casein aggregates (sub-micelles) in the aqueous phase, above a certain critical concentration. These aggregates cause emulsion droplets to flocculate by a depletion mechanism. However, if the same protein or polysaccharide is present in just sufficient quantity to completely saturate the droplet surface, the emulsion may remain kinetically stable for many weeks because of the secondary steric-stabilising layer of biopolymer or because of viscosity-enhanced network formation (Dickinson and Pawlowsky, 1997).

6.4.2 Bridging flocculation

Bridging flocculation normally occurs when a high molecular weight biopolymer at a sufficiently low concentration adsorbs to two or more emulsion droplets, resulting in bridges (McClements, 2005). In general, higher molecular weight biopolymers are expected to provide better protection against flocculation by forming a thick steric-stabilising layer around the emulsion droplets. However, when such a biopolymer is added at low levels, there is a possibility that the biopolymer will attach to the surface of two or more different droplets rather than to the surface of the same droplet. Thus droplets may be bridged together, resulting in flocculation, as shown in Figure 6.4.

The attractive forces between the biopolymer and the droplet surface may be of electrostatic origin and are generally irreversible and relatively stronger than those generated in depletion interactions (Blijdenstein *et al.*, 2004). Generally, when protein–polysaccharide mixtures are used to stabilise an emulsion, low concentrations of polysaccharide may cause polymeric linkages between protein-adsorbed emulsion droplets, thereby leading to bridging flocculation. However, if the same polysaccharide is present at a higher concentration that is sufficient to completely cover the emulsion droplet surface, the emulsion can be stabilised by steric and electrostatic effects. For example, the influence of ι -carrageenan on the properties of bovine serum albumin (BSA)-stabilised emulsion droplets was investigated by Dickinson and Pawlowsky (1997). The emulsion (20.0 vol% oil, 1.7 wt% BSA,

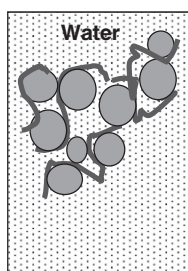


Figure 6.4 Bridging flocculation in an O/W emulsion. Particles approach because bridges are formed by the biopolymer. (The grey and dotted white areas represent oil phase and water phase respectively. The coil structures represent the biopolymer added to stabilise the droplets.)

pH 6.0) without the addition of the polysaccharide was kinetically stable over a period of 10 days. Flocculation, which was not reversible upon dilution, was observed on the addition of low levels of ι -carrageenan (≈ 0.005 wt%), but re-stabilisation of the emulsion was observed at a higher polysaccharide concentration (≈ 0.1 wt%). The flocculation behaviour was explained in terms of a bridging interaction, as addition of ι -carrageenan was not sufficient to completely saturate the entire surface of the emulsion droplets. However, bridging flocculation was replaced by steric and electrostatic re-stabilisation when a higher concentration of ι -carrageenan was added, leading to increased emulsion stability.

6.4.3 Coalescence

Coalescence refers to the fusion of two or more emulsion droplets to form a single droplet of greater volume, as shown in Figure 6.5. Coalescence generally occurs when the stabilising film surrounding the emulsion droplets is either thinned to a certain critical thickness, resulting in film breakage, or ruptured, thus joining emulsion droplets (van Aken, 2004). Generally, emulsions are stable to coalescence as the biopolymer molecules adsorb at the droplet surfaces, forming a dense viscoelastic interfacial layer. However, any extreme processing conditions, such as high shear or enzymatic hydrolysis resulting in significant attrition of the interfacial film, can give rise to gradual agglomeration of bare emulsion droplets, resulting in coalescence and oiling-off. Coalescence has largely been reported in emulsions stabilised by whey protein hydrolysates because of the thinner interfacial film formation and reduced surface viscosity of the predominantly shorter peptides (Agboola *et al.*, 1998; Singh and Dalgleish, 1998). In general, the coalescence of emulsion droplets follows first-order kinetics (Walstra, 1987), which can be expressed by the following equation:

$$\frac{N_t}{N_0} = e^{-K_c t} \quad (6.5)$$

where N_t is the number concentration of emulsion droplets at time t ; N_0 is the initial number concentration of freshly homogenised emulsion droplets (time zero) and K_c is the coalescence rate constant, which is related to the possibility of rupturing of the inter-droplet film and its value equals the slope of a logarithmic plot of (N_t/N_0) versus time t . The degree of coalescence of emulsion droplets is also inversely related to the viscosity of the continuous phase.

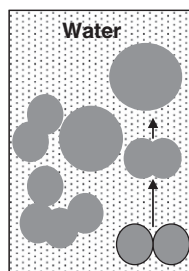


Figure 6.5 Coalescence in an O/W emulsion. Particles approach because rupture of the interfacial layer leads to fusion into a single droplet. (The grey and dotted white areas represent oil phase and water phase respectively.)

6.5 BEHAVIOUR OF EMULSIONS UNDER ORAL CONDITIONS

For the past few decades, colloid scientists have focused on the effects of processing conditions (e.g. heat, high pressure and shear) on the properties of food emulsions (e.g. viscosity, droplet size distribution and phase stability). A great deal of information is available on adsorption phenomena, conformations of the proteins at the oil/water interface, competitive exchange reactions between adsorbed and unadsorbed proteins and factors controlling the rheology and stability of emulsions. In contrast, understanding of the behaviour of emulsions post-consumption is currently limited. The sensory properties of a food product are known to be generally governed by its composition and structure (e.g. flavour, fat content, particle size, microstructure, rheological properties and presence of thickening agents). It has been realised lately that the aroma and the taste perception also depend on the way in which the food behaves in the mouth, that is the physical, biochemical and physiological interactions of the food structure with the oral components during consumption (Malone *et al.*, 2003a, 2003b; Sarkar *et al.*, 2009; Silletti *et al.*, 2007a, 2007b; van Aken *et al.*, 2005; Vingerhoeds *et al.*, 2005, 2008, 2009). Thus, fundamental knowledge and understanding of the complex oral behaviour of food emulsions during mastication and swallowing is critical to successful manipulation of the physical and sensorial attributes of colloidal food systems, such as emulsion stability, creaminess and rate of flavour release.

The mouth is the first chamber of the alimentary canal, where foods are consumed, manipulated and processed both mechanically and biochemically, to safely pass through the pharynx and oesophagus to the stomach. It is the primary step of digestion, considering the action of oral enzymes (amylases). The tongue, palate (hard and soft), epiglottis and lips set the boundaries of the oral cavity (see Chapter 1). Generally, oral cavities from different healthy individuals are similar in their general features and functions, but vary significantly in size (Chen, 2009; Le Révérend *et al.*, 2010). Moreover, the individual characteristics of each subject, such as gender, age, race and physiological condition, play an important role in determining the processing of food in the oral cavity. It has been shown that the typical oral capacity of water is $\approx 30.5 \pm 10.1$ g for adult males and $\approx 25.2 \pm 8.1$ g for adult females (Medicis and Hiiemae, 1998). These values reduce significantly when solid food is consumed. For example, the same authors (Medicis and Hiiemae, 1998) reported that the average weight of banana to fill the oral cavity under normal eating conditions was 18.0 ± 4.9 g for adult males and 13.1 ± 4.0 g for adult females. This suggests that the quantity of food processed in the mouth will depend not only on the individual but also on the physical characteristics of the food consumed.

Food colloids, mostly liquid or semi-solid in nature (emulsions, gels, foams), which are of special interest for this review, can be swallowed as such; thus, the role of the teeth is intuitively minimal. However, the properties and microstructure of a food emulsion undergo a significant change as a result of the complex physical and biochemical events that occur in the human oral regime (Chen, 2009; Malone *et al.*, 2003a, 2003b; Sarkar *et al.*, 2009). For example, in the case of butter, which is a W/O emulsion, melting of the continuous phase followed by phase inversion in the mouth results in destabilisation of the emulsion, allowing the perception of a pleasant creamy mouthfeel and the corresponding flavour release (Norton *et al.*, 2009).

Compared with solid foods, oral processes for liquid emulsions are less well characterised, possibly because the flavour release and the deposition of volatile aromas are driven primarily by tongue movements (Lillford, 2000), which have been reported to be difficult

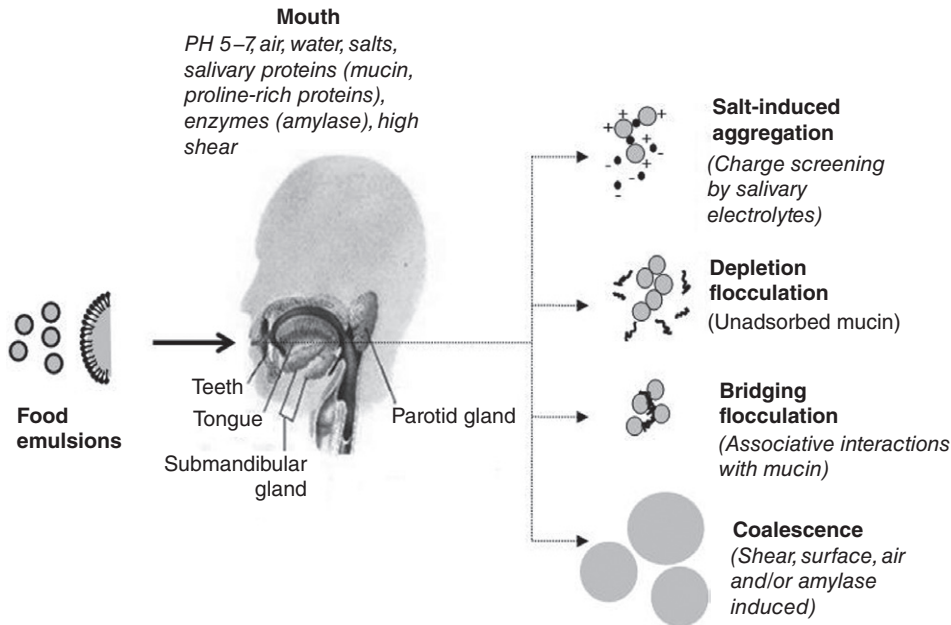


Figure 6.6 A schematic diagram of the possible changes in liquid emulsions during oral processing.

to measure instrumentally without restricting masticatory movements (de Wijk *et al.*, 2003). Moreover, the lubrication and dilution of the liquid food by the saliva, the action of salivary amylases on any starch present in the food and the shearing action within the oral palate may destabilise the system and influence flavour release, depending on the residence time in the mouth.

Figure 6.6 represents the possible interactions of a liquid emulsion with saliva during oral processing. In general, on ingestion, the liquid emulsion is subjected to a range of processing conditions, including mixing with saliva and air, heating or cooling to body temperature, and shear between the teeth, the epithelial surfaces of the tongue and the oral palate. Although it resides in the mouth for a very short period of time, the liquid emulsion is still exposed to various salivary enzymes such as α -amylase and carbonic anhydrase, biopolymers such as mucins, salts of various ionic strengths and a moderate change in pH (Bardow *et al.*, 2000; de Wijk and Prinz, 2005; de Wijk *et al.*, 2004; Glantz, 1997; Malone *et al.*, 2003a, 2003b; Schipper *et al.*, 2007). Of special interest for the behaviour of a liquid emulsion in the mouth are the presence of saliva and the shear effects in the mouth. The oral destabilisation of emulsions as a result of these two important components is discussed in the next sections.

6.5.1 Saliva-induced destabilisation

Human saliva is a highly complex biological fluid, consisting mainly of water ($\approx 99.5\%$), various proteins ($\approx 0.3\%$) and small organic and inorganic compounds (strong and weak ions) that contribute to its buffering capacity, and has a pH of around 6.8 for healthy adults (Aps and Martens, 2005; Gal *et al.*, 2001; Humphrey and Williamson, 2001; Schipper *et al.*, 2007; Zalewska *et al.*, 2000). The inorganic components of saliva contain the usual

electrolytes (sodium, potassium, chloride and bicarbonate) of the body fluids but at different concentrations, making saliva a hypotonic fluid. The proteins in saliva include mainly α -amylase, immunoglobulins, antibacterial proteins, proline-rich proteins, lysozyme, lactoferrin, peptides such as histatins, cystatins and statherin, and highly glycosylated mucin (Amado *et al.*, 2005; Hu *et al.*, 2007; Humphrey and Williamson, 2001). Generally, the secretion of human saliva varies from 0.3 to 7 mL of saliva per minute with about 500–1500 mL of saliva per day. The quantity, overall composition and biochemical properties of unstimulated human saliva vary enormously, depending on the type and size of the salivary gland, duration, the stimulus, diet, drugs, age, sex, blood type, health status and other physiological factors. Detailed physiological analyses of human saliva are given in Chapter 3 of this book and can be found in a number of relevant reviews (Aps and Martens, 2005; Schipper *et al.*, 2007; Zalewska *et al.*, 2000).

Intuitively, it might be expected that the pH, the ionic composition and the organic compounds present in saliva could significantly influence the behaviour of an emulsion. Recent studies in our laboratory (Sarkar *et al.*, 2009) investigated the interaction of an O/W emulsion stabilised by lactoferrin with an artificial saliva composition. Initially, lactoferrin formed a stable cationic emulsion at neutral pH. However, on mixing with artificial saliva containing various salivary salts, the emulsion underwent extensive droplet aggregation, which was largely due to screening of the positive charges of the lactoferrin molecules on the droplet surface by the negatively charged electrolytes, such as chlorides, citrates and phosphates, present in the artificial saliva composition.

Among the organic constituents of saliva, the most prominent salivary enzyme, that is α -amylase, plays an important role in the initial hydrolysis of starch-containing foods before swallowing (Evans *et al.*, 1986; Wakim *et al.*, 1969). When a starch-thickened food product is consumed, it is mixed with the saliva in the mouth, the α -amylase leads to a fast digestion of the starch into maltose and this breakdown immediately affects the perceived starch viscosity (de Wijk *et al.*, 2004, 2006; Engelen, *et al.*, 2003a, 2003b; Heinzerling *et al.*, 2008). For example, emulsions containing 10 wt% sunflower oil stabilised by starch-based emulsifiers such as octenylsuccinate starch (clear gum) underwent rapid irreversible saliva-induced coalescence, which was predominantly due to the hydrolysis of the starch-based interfacial layer by amylase (Dresselhuis *et al.*, 2008c). Breakdown of the adsorbed starch layer by salivary α -amylase resulted in a much thinner and weaker interface, which consequently might have ruptured, leading to gradual accretion of emulsion droplets to larger coalesced droplets ($>100\mu\text{m}$ in size).

One of the most important organic constituents of saliva, mucin (MUC5B and MUC7), plays an important role in emulsion destabilisation because of its negative charge at neutral pH. Mucins are generally highly glycosylated extracellular proteins containing ≈ 50 – 80% oligosaccharides, mainly *N*-acetylgalactosamine, *N*-acetylglucosamine, fucose, galactose and sialic acid (*N*-acetylneuraminic acid), and traces of mannose and sulphate attached by *O*-glycosidic bonds to the hydroxyl groups of serine and threonine residues of the protein backbone, finally clustered in a ‘bottle brush’ arrangement (Bansil and Turner, 2006; Thomsson *et al.*, 2002). Mucins generally account for ≈ 10 – 25% of the total salivary protein, with molecular weights ranging from 0.5 to 20×10^3 kDa.

MUC5B is the major multimeric fraction of salivary mucin, and is responsible for a weak gel structure formation of the mucus layer as well as the bulk fluid of quite large hydrodynamic size (Bolscher *et al.*, 1995; Strous and Dekker, 1992; Wickström *et al.*, 2000). The concentration of high molecular weight mucin (MUC5B) in whole saliva varies from approximately 30 to $500\mu\text{g/mL}$, depending on the stimulus. Gelation of mucin is

attributed mainly to the association of the mucin molecules via hydrophobic bonds, carbohydrate–carbohydrate interactions and calcium-induced cross-linking (Bromberg and Barr, 2000; Strous and Dekker, 1992; Waigh *et al.*, 2002). This weak gel character, caused by the entanglement of mucin molecules, is mainly responsible for the typical viscoelastic and shear-thinning behaviour of the saliva (Bansil and Turner, 2006; Rayment *et al.*, 2000; Schipper *et al.*, 2007). This has been further proved by studies showing that the viscosity of saliva from parotid glands, which does not contain high molecular weight mucins, is shear rate independent, with a viscosity slightly higher than that of water (van der Reijden *et al.*, 1993; Veerman *et al.*, 1989).

In recent years, there has been considerable progress in establishing the mechanisms of interactions between food emulsions (various proteins and surfactant-stabilised emulsions) and saliva (both unstimulated human saliva and artificial saliva), either by *in vivo* methods, that is by taking the emulsion in the mouth, or by *in vitro* methods, that is by mixing the emulsion with the saliva (Sarkar *et al.*, 2009; Silletti *et al.*, 2007a, 2007b, 2007c; van Aken *et al.*, 2005; Vingerhoeds *et al.*, 2005). By consolidating the results of independent studies, it can be inferred that the emulsions generally underwent different degrees and types of flocculation in the presence of saliva, largely driven by depletion, van der Waals' forces and/or electrostatic interactions between emulsion droplets and salivary proteins, depending on the net charge of the emulsion droplets and the presence of other charged molecules in the saliva (Figure 6.7).

6.5.1.1 Neutral or negatively charged emulsion–saliva interactions

The oral behaviour of commercial dairy emulsions (1.5 and 3% fat homogenised pasteurised milk and 40% whipped cream) was investigated in an interesting *in vivo* study (van Aken *et al.*, 2005). Emulsions were taken in the mouth by human subjects for 1 min and subsequently spat out. Droplet flocculation with loose slimy aggregates was reported in these emulsion-spat-out mixtures. To investigate the aggregation mechanism, *in vitro*

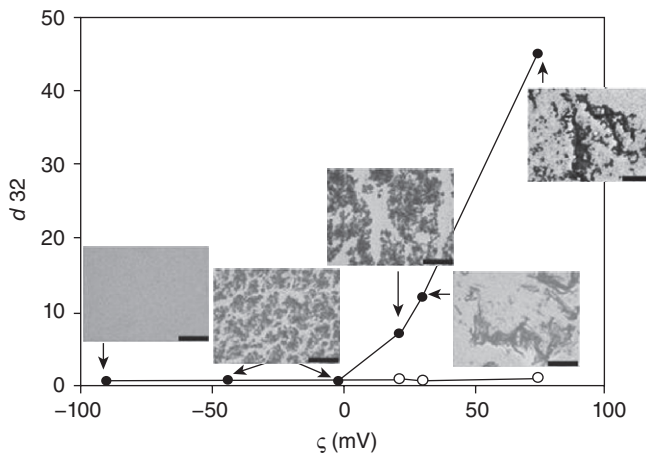


Figure 6.7 Particle size (d_{32} values) of the emulsions (○) and the emulsion/saliva mixtures (●) after dilution in water as a function of the ζ -potential of the emulsions. Light microscopy pictures show the morphology of the corresponding mixtures (scale bar 200 μm) of the samples before dilution. Reproduced from Silletti *et al.* 2007c with permission.

studies on the effects of mixing unstimulated human saliva with O/W emulsions (40 wt% sunflower oil) stabilised by 1.0 wt% of neutral surfactant (polyoxyethylene sorbitan monolaurate (Tween 20)), negatively charged surfactants (sodium dodecyl sulphate (SDS), diacetyl tartaric acid ester of monoglyceride (Panodan)) and proteins (whey protein isolate (WPI), β -casein, sodium caseinate and β -lactoglobulin) were conducted (Silletti *et al.*, 2007b; Vingerhoeds *et al.*, 2005). Highly negatively charged emulsions, that is SDS- and Panodan-stabilised emulsions, remained stable in the unstimulated human saliva. This behaviour was explained on the basis of dominant repulsive forces in the negatively charged emulsion, which prevented close approach of the droplets.

In the case of weakly negatively charged emulsions (β -lactoglobulin at pH 6.7, WPIs, sodium caseinates, β -casein) and neutral emulsions (Tween 20), rapid reversible flocculation was observed, with the flocs being disrupted upon dilution and shear, which was assumed to be due to depletion flocculation (Sarkar *et al.*, 2009; Silletti *et al.*, 2007b; Vingerhoeds *et al.*, 2005). Rheological measurements further confirmed shear-thinning behaviour as a result of gradual break-up of the aggregates. As mucin is a negatively charged polymer, it was not expected to interact with the anionic emulsion droplets; thus, the presence of unadsorbed mucin molecules further contributed to the pseudoplastic behaviour because of the stretching of the random coil mucin molecules in the direction of the flow. This was further supported by a study in our laboratory, which showed that a β -lactoglobulin-stabilised emulsion (20 wt% soy oil, 1.0 wt% β -lactoglobulin) underwent droplet flocculation when mixed with an artificial saliva composition containing a model mucin (pig gastric mucin) (Sarkar *et al.*, 2009). The experimental observations of non-Newtonian rheological behaviour of the β -lactoglobulin emulsion–artificial saliva mixture (10 wt% soy oil, 0.5 wt% mucin), aggregated confocal micrographs and the reversibility of flocculation on dilution of the aggregated emulsion–artificial saliva mixture were indicative of depletion flocculation. Hence, in the case of weakly negatively charged emulsions, saliva induces almost instantaneous flocculation. Because of the high molecular weight and the radius of gyration of mucins, depletion forces play an important role in the saliva-induced aggregation. This rapid depletion flocculation in weakly negatively charged emulsions was shown to be largely dependent on the mucin concentration (critical mucin concentration of 0.4 wt%) present in the saliva.

Although negatively charged mucin was reported to be predominantly responsible for inducing flocculation of the emulsions, some irreversible aggregation was reported for WPI- and β -lactoglobulin-stabilised emulsions even in the presence of parotid saliva (which does not contain mucin) (Vingerhoeds *et al.*, 2005). Furthermore, the critical mucin concentration that was required to induce droplet flocculation in the *in vitro* study was much higher than the average mucin content in human saliva (generally 0.02 wt%). Therefore, it appears that salivary polymeric components other than mucin, such as macromolecular salivary micelles (Rykkeet *et al.*, 1995; Soares *et al.*, 2004) or the proline-rich proteins (which are best known to interact with polyphenolic compounds in foods such as salivary tannins, resulting in astringency) (Lu and Bennick, 1998), present in saliva might also contribute to flocculation phenomena in the oral environment by some unknown mechanisms.

6.5.1.2 Positively charged emulsion–saliva interactions

According to the recent literatures (Sarkar *et al.*, 2009; Silletti *et al.*, 2007a), there are attractive interactions between the positively charged surfactants adsorbed at the interface and the negatively charged biopolymers present in saliva. When positively charged

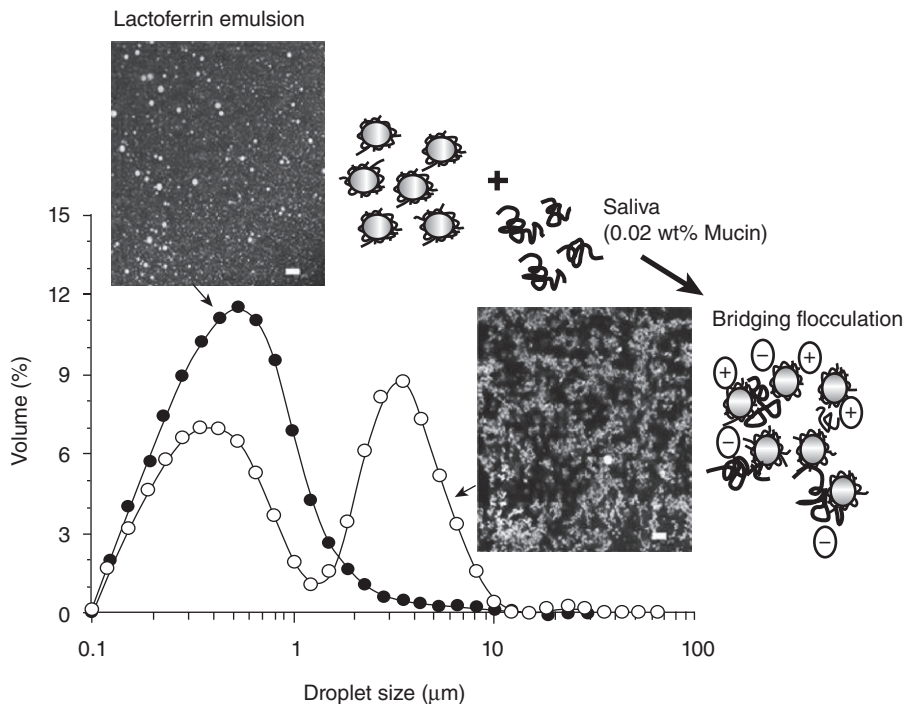


Figure 6.8 Droplet size distributions and confocal micrographs of an emulsion made with 20 wt% soy oil, 1.0 wt% lactoferrin (●) and an emulsion mixed with artificial saliva containing 0.02 wt% mucin (○). The scale bar in the confocal micrographs represents 10 μm . The large shaded circles coated with thin coil structures represent lactoferrin-stabilised emulsion droplets and the grey thick structures represent mucin molecules.

emulsions, that is oil/water interfaces stabilised by lysozyme, β -lactoglobulin at pH 4.3 and cetyltrimethylammonium bromide, were mixed with whole unstimulated human saliva (Silletti *et al.*, 2007b), irreversible aggregation was observed, which was attributed to a bridging interaction induced by electrostatic interaction between negatively charged mucins and positively charged interfacial layers adsorbed at the droplet surface.

Further insight into the flocculation mechanism for positively charged emulsions was gained by conducting an *in vitro* study in our laboratory using a mixture of lactoferrin-stabilised emulsion and artificial saliva (Sarkar *et al.*, 2009). Microstructural analysis demonstrated the presence of strong flocs and, correspondingly, light-scattering measurements showed bimodal size distributions that did not completely break up into single droplets upon dilution and shear (see Figure 6.8). This corresponded to a sharp decrease in positive surface charge of the lactoferrin emulsion droplets on addition of saliva, confirmed by ζ -potential measurements, which was attributed to the electrostatic binding between anionic mucin present in the saliva and positively charged lactoferrin-coated emulsion droplets. This is typical of an emulsion system displaying bridging flocculation in which the bonds are relatively strong and irreversible. Previous oral deposition studies conducted with pig gastric mucins also reported the adsorption of a positively charged chitosan emulsion on to the mucin films, indicating electrostatic interactions between mucins and positively charged emulsion droplets (Malone *et al.*, 2003a).

Additional information on the flocculation of positively charged emulsions was obtained by studying the interaction of lysozyme-stabilised O/W emulsions (20 wt% sunflower oil, 1.0 wt% lysozyme) with whole human saliva. Silletti *et al.* (2007a, 2007c) showed the formation of complexes between salivary proteins and lysozyme not only adsorbed at the oil/water interface but also in the solution, detected using confocal microscopy. This finding, of lysozyme–saliva complex formation in solution, strongly suggested that complex formation between lysozyme-coated droplets and salivary proteins caused emulsion flocculation and also indicated that the salivary proteins may interact with the lysozyme molecules available in the continuous phase of the emulsion. However, it is not clear whether or not such lysozyme–saliva complex formation in the continuous phase of an emulsion–saliva mixture contributes to emulsion flocculation.

In addition to mucin, there are other negatively charged proteins in saliva, such as cystatins, serum albumins, different isoforms of α -amylase (isoelectric point (pI) values ranging from 5.9 to 7.2), that can also contribute to the bridging flocculation of positively charged emulsions (Silletti *et al.*, 2007a; Yao *et al.*, 2003), although their concentration in whole unstimulated saliva is considerably less than that of mucin. Silletti *et al.* (2007c) recently identified the saliva components at the lysozyme-stabilised oil/water interfaces using infrared spectroscopy, Western blotting and gel electrophoresis. The authors reported that the interaction between emulsion droplets and saliva is limited not only to mucins (MUC5B and MUC7) but also to other salivary proteins of molecular weight in the range 10–100 kDa, such as polymeric immunoglobulins, amylase and low molecular weight protein fractions (<20 kDa). Although the salivary components were identified, the driving mechanism of interaction of each salivary component with the emulsifier layer at the oil/water interface still remains to be elucidated.

6.5.2 Shear-induced destabilisation

As well as the saliva, the role of tribology in the field of the oral processing of food is gradually gaining importance (see Chapter 12). Upon swallowing a liquid food, the tongue is pressed against the oral palate, giving a frictional effect (Malone *et al.*, 2003a), and the saliva provides the lubrication (Vingerhoeds *et al.*, 2009). Because of these complex shear effects of the oral surfaces, emulsion droplets show rapid coalescence in the mouth, depending on the type and the amount of emulsifier initially present to stabilise the emulsions, the droplet size and the fat type within the emulsion droplets (Dresselhuis, *et al.*, 2008c; van Aken *et al.*, 2003, 2005, 2007).

Dresselhuis *et al.* (2008c) conducted a detailed experiment to show that protein-stabilised O/W emulsions that are susceptible to shear-induced coalescence (such as the presence of an insufficient amount of protein as emulsifier to completely cover the droplet surface or the presence of fat crystals within the emulsion droplets) have an increased tendency to coalesce during in-mouth shear processing. In this study, ‘very stable’ emulsions (sunflower oil stabilised by a mixture of 0.95 wt% WPI and 0.05 wt% sodium caseinate as emulsifier, heated after homogenisation to increase the adsorbed layer thickness), ‘stable’ emulsions (prepared using WPI and containing sunflower oil as the fat phase) and ‘unstable’ emulsions (made using palm fat (solid) as the fat phase and/or lower amounts of WPI) were prepared. In the case of the ‘unstable’ emulsion with the lower WPI content, comparable protein surface coverage was achieved by manipulating the concentration of WPI as a function of the droplet size: 0.3 wt% WPI for smaller droplets and 0.1 wt% WPI for larger droplets (0.2 wt% WPI when solid fat was used). These emulsions were sheared in the

optical tribological configuration (OTC), that is between a piece of the dorsal surface of a pig's tongue and glass, at a speed of 80 mm/s and a load of 0.5 N. Emulsions were also orally processed by six human subjects and were characterised using spat-out samples. In all cases, the droplet size increased when the emulsions were sheared between the tongue and glass surfaces. As expected, the 'very stable' emulsions (WPI- and sodium-caseinate-stabilised) and the 'stable' emulsions (1.0 wt% WPI) did not show any in-mouth coalescence. Oral processing of emulsions stabilised with less emulsifier did result in larger coalesced droplets. Rheological measurements showed that emulsions containing solid fat (palm fat) had a greater tendency to cluster together, resulting in larger structures (partial coalescence) than for emulsions containing sunflower oil. However, no significant increase in droplet size was reported in the spat-out experiments, which was probably because solid palm fat instantly melted in the mouth (37 °C), well before any partial coalescence could occur. It is worth noting here that even contact with the tongue surface (without shearing) resulted in an increase in the average droplet size in the unstable emulsions, suggesting that surface-induced coalescence also plays an important role in destabilisation.

Despite a number of attempts to mimic the oral surfaces and shear patterns in the mouth to understand the oral behaviour of emulsions, successful simulations have not yet been achieved. *In vitro* friction testers using tetrafluoroethylene (PTFE) and zirconium respectively as pin-on-disk (Lee *et al.*, 2004) or a steel ball and silicon rubber as ball-on-disk (Malone *et al.*, 2003a) set-ups have been built to understand the adhesion, friction and lubrication. Several authors have tried to modify the artificial surfaces by fabricating roughness (Cassin *et al.*, 2001). Because of the large dissimilarities between artificial surfaces and human oral mucosa, pig's tongue has also been used to elucidate the effect of surface characteristics on the emulsion behaviour (Dresselhuis *et al.*, 2007, 2008b, 2008c). In a recent study, Dresselhuis *et al.* (Dresselhuis *et al.*, 2008b) compared the surface-induced lubrication behaviour and the frictional effects between a pig's tongue surface and a modified polydimethylsiloxane (PDMS) surface by shearing a concentrated protein-stabilised emulsion (40 wt% O/W, stabilised by 1 wt% WPI) between both of the surfaces. Because of the typical surface roughness of pig's tongue, attributed to the presence of papillae, significant differences were reported in the occurrence of coalescence between shearing with a pig's tongue surface and shearing with PDMS surfaces (Dresselhuis *et al.*, 2008b). The emulsion with an average droplet size of 2.4 µm, sheared between pig's tongue and glass with the tongue tissue as the upper surface, showed coalescence of droplets and oil release because of the roughness of the cone-shaped papillae structure present on the tongue. However, no large droplets were observed on shearing the same emulsion between smooth PDMS rubber and glass under the same load of 0.5 N. This indicated that coalescence of emulsion droplets in the mouth is regulated not only by shear but also by the surface roughness of the oral mucosa. The use of animal tissues for tribological studies might not be practical because of individual variations in tissue structure, limited availability, less reproducibility and fast tissue degradation.

To summarise, the occurrence of coalescence in the mouth depends on the characteristics of the emulsion (droplet size, interfacial layer, amount of emulsifier and type of fat), the shear forces and the characteristics of the oral mucosa. Apart from saliva and shear-induced destabilisation, air is also entrapped between the food structures on consumption of food and might result in spreading of the droplets on the air/water interface, resulting in air-induced coalescence in the mouth (Dresselhuis *et al.*, 2008c; van Aken *et al.*, 2005).

6.5.3 Relating oral destabilisation to sensory perception

As remarked in the previous sections, the destabilisation behaviour of emulsion droplets on exposure to an oral environment could involve bridging or depletion type flocculation, salt-mediated aggregation or coalescence induced by saliva (salivary amylases), shear, surface and air. These droplet interactions within the saliva–emulsion mixture would result in alteration of the microstructure, the droplet size distribution, the volume fraction of the dispersed phase, the rheology behaviour, the surface-to-volume ratio and the oil released during oral processing. These changes in emulsion properties are expected to markedly affect the perceived sensorial and textural attributes (Kokini and Aken, 2006; Vingerhoeds *et al.*, 2008, 2009). Furthermore, an increase in viscosity, either by flocculation or by the addition of thickening agents such as starch, guar gum or carrageenan, plays an important role in providing a creamy mouthfeel for fluid and semi-solid foods (Akhtar *et al.*, 2005; Kokini and Aken, 2006; Tarrega and Costell, 2006; Vingerhoeds *et al.*, 2009).

An attempt is made to summarise the relevance of the colloidal destabilisation of emulsion droplets in the oral environment to sensory perception by classifying into two broad categories (i.e. droplet flocculation and coalescence) in the following subsections. The discussion focuses mainly on the physico-chemical characterisation of the emulsions after oral processing and sensory analysis.

6.5.3.1 Droplet flocculation

As noted previously, emulsions flocculate reversibly or irreversibly on mixing with saliva. To understand the effect of this aggregation behaviour on sensory perception, Vingerhoeds *et al.* (2008) initially compared the sensory perception of the reversible flocculation in whey protein emulsions at neutral pH with the irreversible flocculation of the same emulsions at acidic pH. On consumption, the whey-protein-stabilised emulsions showing bridging flocculation at acidic pH were perceived as having a higher degree of dryness, astringency and roughness compared with those at neutral pH. However, it was not clear whether the perception was related to the flocculation type or to the impact of low pH on the perception itself.

To better understand the role of flocculation in saliva, Vingerhoeds *et al.* (2009) compared the sensory perception of emulsions stabilised by lysozyme with that of emulsions stabilised by whey proteins at neutral pH (see Figure 6.9). Interestingly, irreversible bridging flocculation in lysozyme-stabilised emulsions, as described previously, was perceived orally as astringent, dry and rough. Moreover, oil and protein retention on the tongue surface after oral processing and rinsing the mouth with water was shown to be much higher for the lysozyme-stabilised emulsions. In contrast, negatively charged emulsions, such as those stabilised by whey proteins or β -lactoglobulin at neutral pH, showed reversible (depletion) flocculation, had little retention in the mouth and revealed creamy and fatty perception in the mouth. This perception of dryness and roughness in the mouth for positively charged emulsions was suggested to be largely similar to the polyphenol–saliva interactions, leading to the precipitation of lubricating salivary proteins and the loss of elastic behaviour of the saliva, resulting in perceived astringency, dryness and a rough mouthfeel (de Freitas and Mateus, 2002; Lu and Bennick, 1998; Mateus, *et al.*, 2004; Prinz and Lucas, 2000; Rossetti *et al.*, 2008; Siebert and Chassy, 2004).

In the case of whey-protein-stabilised emulsions, the enhanced emulsion viscosity as a result of reversible depletion flocculation was perceived as improved thickness and

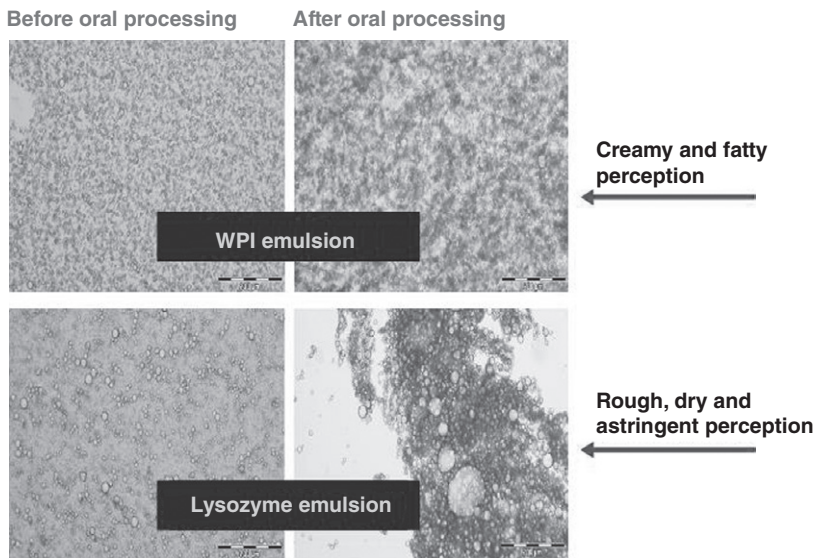


Figure 6.9 Microscopic images of 10% oil containing WPI- and lysozyme-stabilised emulsions before and after oral processing (scale bar 200µm). Reproduced from Vingerhoeds *et al.*, 2009, pp.773–785, with permission from Elsevier.

fattiness. It is generally considered that the viscosity of a product is directly related to perceived thickness. Based on the large increase in viscosity because of irreversible flocculation of lysozyme-stabilised emulsions in the presence of saliva, it might be expected that there would be a significant enhancement in perceived thickness and creaminess, but this did not happen. The higher viscosity of the lysozyme-stabilised emulsions (due to irreversible flocculation) compared with the whey-protein-stabilised emulsions after oral processing was overshadowed by the strong perception of dryness and roughness, because of possible complexation of lysozyme with salivary proteins, resulting in small precipitates ($\approx 10\mu\text{m}$), which were sensed as gritty particles. This complex formation (caused by the binding of lysozyme to the salivary proteins) possibly removes salivary proteins from the saliva and/or mucus layer from the oral mucosa and thus reduces the lubricating properties of the saliva and the oral surfaces, leading to an astringent after feel. Interestingly, the addition of thickeners such as 1.0 wt% guar gum further promoted the thickening perception for whey-protein-stabilised emulsions, by viscosity enhancement (Vingerhoeds *et al.*, 2009). Furthermore, it reduced the typical astringent sensation of irreversibly flocculated positively charged emulsions, possibly by increasing the viscosity and acting as a substitute for the lubricating behaviour of the saliva. Hence, the addition of a polysaccharide might lower the difference in perception between both types of flocculated emulsions, either by adhering to the tongue, providing lubrication, or by increasing the viscosity (van Vliet *et al.*, 2009; Vingerhoeds *et al.*, 2009).

6.5.3.2 Droplet coalescence

Coalescence or oiling-off is expected to significantly affect the perception of fat-related attributes, such as creaminess and fatty mouthfeel. As most of the food flavour compounds

are fat soluble, coalescence may affect the release of aroma compounds; this flavour release is reported to correlate with the perception of fatty mouthfeel (Doyen *et al.*, 2001; Malone *et al.*, 2003b; Richardson-Harman *et al.*, 2000; Yackinous and Guinard, 2000).

In vitro studies have shown that coalescence leads to a decrease in the friction of rubber surfaces (Dresselhuis *et al.*, 2007) and enhanced emulsion spreading on glass surfaces (Dresselhuis *et al.*, 2008a). This reduced friction might lead to an increased retention of emulsion droplets at the tongue surface and can result in a creamier mouthfeel. Recent studies (Dresselhuis *et al.*, 2007, 2008b, 2008d) confirmed that droplet coalescence during oral processing can result in higher fatty perception by possibly forming a fatty coating on the oral mucosa because of the spreading of larger coalesced droplets on the tongue surface, resulting in a reduction in the perceived friction between the tongue and the oral palate. In general, oil release from an emulsion, and thus fat-related attributes, might increase with decreasing stability of the emulsion towards coalescence, either because of the lowering of the adsorbed amount of protein at the droplet surface (Dresselhuis, 2008d), the use of an amylase-sensitive adsorbed layer (Dresselhuis *et al.*, 2008c), or because of partial coalescence (Benjamins *et al.*, 2009). For example, Dresselhuis *et al.* (2008c) showed that emulsions stabilised by amylase-sensitive modified starch, which coalesced rapidly to large droplets ($>100\mu\text{m}$) because of shear- and saliva-induced oral processing, demonstrated higher scores for fat-related sensory attributes such as fattiness, creamy mouthfeel and thickness. This increased perception of fattiness and smoothness with the oil release in the mouth was proposed to be due to an enhanced aroma release, caused by the occurrence of coalescence. Moreover, these authors (Dresselhuis *et al.*, 2008c) also suggested that a lower sensed friction because of the lubricating behaviour of the oil released during in-mouth coalescence may result in a creamy perception.

Coalescence results in the generation of larger sized droplets. Although droplet size is an important characteristic of an emulsion, the direct effect of the droplet size (size range $\approx 0.5\text{--}6.0\mu\text{m}$) on sensory perception such as thickness, creaminess and fattiness was reported to be minor for low viscosity emulsions (Vingerhoeds *et al.*, 2008). However, droplet size significantly affects the stability of the emulsion to droplet flocculation and coalescence, which would indirectly affect the perceived taste. For example, Kilcast and Clegg (2002) showed that the perceived thickness and the creamy texture of artificial cream were improved with increasing droplet diameter (size range $\approx 0.5\text{--}2.8\mu\text{m}$), which was due to the slight aggregation of the larger cocoa butter droplets, resulting in enhanced viscosity. Droplet size has also been correlated with friction within the oral surfaces (de Wijk and Prinz, 2005). They showed that smaller droplets, being less deformable than larger sized droplets, result in comparatively smaller contact areas and consequently in reduced friction. This reduced friction might result in significantly increased sensations of creaminess, fattiness, thickness, slipperiness and smoothness. Furthermore, increased droplet size has been shown to be related to the enhanced release of flavour compounds from the oil droplets (van Ruth *et al.*, 2002).

6.6 CONCLUDING REMARKS

The mouth is the first point of contact between food and the human digestive system. In the mouth, food is subjected to several mechanical and biochemical processes. Taste and texture of the food are perceived and the state of the food is set for further digestion after swallowing: everything that happens in the mouth affects subsequent digestive processes.

Saliva plays a crucial role acting as an interface between food particles and the surfaces of the mouth, acting as an intermediary for flavour sensation, and as a physical lubricant, contributing to mouthfeel.

Upon ingestion, food emulsions can undergo destabilisation, due to coalescence and/or bridging or depletion-type flocculation, depending on the ratio of saliva to emulsion, the emulsifier type, shear, pH and ionic conditions. This destabilisation behaviour appears to affect the emulsion perception, as the sensory attributes, such as creaminess, are governed not only by the initial composition of the emulsions but also the state of emulsion in the mouth. However, further understanding is required on the interactions of emulsion droplets with oral surfaces, and how the droplets deposited on oral surfaces are perceived by the sensory panels. A more detailed understanding of the interactions of emulsion droplets/particles with the salivary components and taste sensors in the mouth is also needed. Such knowledge may be useful for development of new emulsion products with specific flavour and texture sensations.

The fundamental mechanisms of interactions could be established in systematic model emulsion studies *in vitro* but there will be challenges in predicting what happens under real physiological oral conditions and when real complex foods are ingested. Because of the variability in the composition of saliva across individuals and with age, careful *in vitro* systems that mimic real biological systems need to be developed. Moreover, studies to develop methods to measure astringency, creaminess and so on more accurately need to be carried out. The insights obtained from *in vitro* analyses of model emulsion systems, together with further research involving proper measurement of sensory attributes, will be required to test the efficacy of complex emulsion structures.

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7 Bolus Formation and Swallowing

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7.1 INTRODUCTION

Bolus formation and swallowing are integrated oral actions of an eating process. Bolus formation is essentially a restructuring process which, with the incorporation of saliva, converts orally processed food particles into a ready-to-swallow status; whilst swallowing is a transportation process which conveys the bolus (or saliva for non-eating cases) from the oral cavity through pharynx and oesophagus to the stomach. An eating process may involve a few swallowing actions, at least one interval and one final swallow. The final swallow is sometimes called oral clearance and marks the completion of a whole eating process. Swallowing itself has a limited influence on the sensory perception and appreciation of a food. The most important issue concerning a swallowing process is the ease and safe flow of food boluses through the food passageway. Despite the fact that bolus formation and swallowing are seen by many individuals as oral routines which require little effort, these oral actions can be highly challenging and hazardous to some vulnerable individuals (elderly, infants, patients, etc.) and pose health risks to these consumers. This chapter will review recent research progress on the fundamentals of bolus formation and swallowing. The main focus of the review will be on the underpinning food physics and oral physiology principles of bolus formation and swallowing, including stages of bolus swallowing, the dynamics of bolus formation, critical properties of a food bolus, and more importantly the critical criteria triggering a swallowing action.

7.2 MECHANISMS OF SWALLOWING

7.2.1 Stages of swallowing

Swallowing is a highly complicated oral action which involves a series of simultaneous and coordinated contractions and inhibitions of responsible muscles located around the mouth and at the tongue, larynx, pharynx and oesophagus regions. The physiological process of swallowing has been conventionally described in stages or phases representing

the anatomic regions traversed by the bolus. Of the various models of swallowing, the three-stage theory is probably most commonly accepted due to its illustrative simplicity (Miller, 1982). According to this model, a swallowing process can be divided into an oral phase, a pharyngeal phase and an oesophageal phase. The oral phase is normally seen as voluntary, while the subsequent phases are considered to be reflex responses. It should be noted that, even though this model gives clear-cut three phases, much evidence suggests that the physiological components of a swallowing process overlap and are interdependent as the bolus traverses the regional phases (oral, pharyngeal and oesophageal). Despite its disparity from true facts, the three phase description is still favoured for the purposes of illustrative convenience and is frequently acknowledged in the literature.

7.2.1.1 *The oral phase*

The oral phase of swallowing can be further divided into two sub-phases: oral preparatory and oral propulsion. The oral preparatory phase is simply a phase of preparation or conversion of food into a swallow-able status. The mechanisms involved in this phase can be very different, and are highly dependent on the microstructure and mechanical nature of the food. For a liquid food, no chewing action is required and oral preparation is relatively simple. A liquid food is held in the anterior part of the floor of the mouth after its ingestion. The oral cavity is sealed posterior by the contact between the soft palate and the tongue to prevent the liquid from leaking into the oropharynx, so that the food can be tasted and appreciated as well as buffered by saliva and thermally equilibrated to the body temperature before being swallowed. At this stage, leakage of liquid food into the oropharynx is not wanted. However, there is strong evidence that liquid leakage is possible and it is believed that the possibility of liquid leakage increases with ageing (Leder and Murray, 2008). For a solid or semi-solid food, mastication and oral transportation have to be involved in the oral preparatory stage. The tongue moves cyclically in association with lower jaw movement. More importantly, there is no posterior sealing of the oral cavity, permitting open communication between the oral cavity and the pharynx. Therefore, aroma produced from chewing solid food can move freely into the nasal cavity.

Stage II transportation occurs simultaneously with the mastication process (see Chapter 4 for food oral management). When a portion of the food becomes suitable for swallowing, it will be placed on the tongue surface and propelled (pushed) back through the fauces to the oropharynx region. This backward pushing is achieved by the tongue–palate contact, squeezing food particles backward along the palate. Triturated food particles accumulate gradually on the pharyngeal surface of the tongue towards the valleculae. This could be seen as a process of bolus accumulation and would normally last for few seconds or longer for normal healthy individuals. During this stage, the mechanoreceptors, chemoreceptors and thermoreceptors in the oral cavity, tongue and pharynx provide essential information for bolus identification and for its suitability of swallowing (Ertekin and Aydogdu, 2003).

The oral propulsion phase is often seen as the beginning, or the triggering point, of a swallow. To trigger a swallowing action, the mouth has to be firmly closed externally, with lips sealed and teeth in centric occlusion position. The tip (as well as the edge) of the tongue rises, touching the ridge of the hard palate just behind the upper teeth, while the posterior tongue drops to open up the back of the oral cavity. The tongue–palate contact expands from anterior to posterior, forcing the food bolus to move backwards along the palate into the pharynx. It is critically important that triggering a swallow is well-timed. Improper timing will cause serious health risks during the pharyngeal and oesophagus phases.

Coughing and choking are the two most common consequences of an improperly timed swallow or swallowing an inappropriate bolus. Although when to trigger a swallow is obvious to healthy individuals, what triggers this seemingly unconscious action is not as clear as it appears to be and remains a main research topic for clinical researchers, oral physiologists and food scientists.

7.2.1.2 The pharyngeal phase

The pharyngeal phase of swallowing is highly interrelated to the oral phase and the distinction between the two is often not very clear. This may be because that the two regions are functionally integrated, even though anatomically separated. From the point of view of safety, the pharyngeal phase is probably most critical. Bolus flow at this stage is most complicated due to a shared pathway by the respiratory and gastrointestinal tracts. The pharyngeal region is a joint connection of multi-passageways open to the oral cavity, the nasal cavity, the larynx, and the oesophagus. In order to have a safe swallow, the air passageway linking the nasal cavity and the larynx has to be sealed off and the food passageway connecting the oral cavity and oesophagus has to be switched on swiftly (see Figure 7.1) (Matsuo and Palmer, 2008). To switch different passages off and on, highly coordinated muscle actions are required, either simultaneously or in proper sequential order. Some specific features during this phase are highlighted below:

- The air path is temporarily sealed off. The soft palate elevates and contacts the lateral and posterior walls of the pharynx, closing off the nasopharynx to prevent the bolus from entering the nasal cavity. The larynx is elevated by suprahyoid and submental muscles and the epiglottis falls back functioning as a passive cap over the larynx to seal it off. Proper and timely sealing of the larynx is most essential. Most hazards and health risks associated with swallowing are due to the improper sealing of the larynx, causing food leakage into the respiration system.
- The food bolus should have gained energy and speed from the squeezing action of the tongue and is subject to significant shear and extensional deformation as it flows out from the oral cavity and then into the oesophagus. Therefore, proper flow-ability and proper stretch-ability are most desirable in order to have a smooth bolus flow.

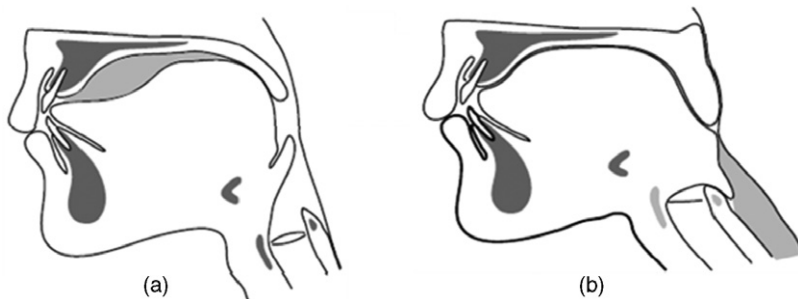


Figure 7.1 The switch off and on of the air passageway and food passageway before (a) and during (b) swallowing. During swallowing, the larynx was lifted and capped to cut off airway, and the soft palate was pressed against the back wall of the pharynx to seal off the nasal cavity. The bolus (highlighted in light grey) was forced into the oesophagus. Modified from Matsuo and Palmer, 2008, with permission of Elsevier.

- While the air path is sealed off, the upper oesophageal sphincter (UES) relaxes and opens up to allow the bolus to enter into the oesophagus. Once the tail of the bolus flow passes through the sphincter, the pharyngeal phase of swallowing is considered to be completed and the sphincter closes. The bolus passageway is then switched off and the air passageway opens up again.

The upper oesophageal sphincter (UES) can be seen as a controlling point for a bolus flow, like a valve. Its opening diameter has a significant influence on bolus flow. It is believed that UES opening is either controlled by coordinated muscle relaxation or forced opening due to the elevated bolus pressure. The exact controlling mechanism of UES opening and the size of opening are yet to be determined.

The velocity spectrum of bolus flow in the pharynx has been of great interests to both food scientists and clinical researchers. One general consensus is that the speed of swallow is highly food-dependent. Hasegawa *et al.* (2005) used ultrasonic pulse Doppler to measure flow speed of boluses composed of water, yoghurt, as well as gelatine and gellan gels. They observed an average speed of around 0.1 m/s for boluses of semi-solid foods, an increased speed of around 0.2 m/s for fluid yoghurt, and a maximum velocity of 0.5 m/s for water. Miquelin *et al.* (2001) used a biomagnetic method to determine pharyngeal bolus flow and observed a pharyngeal transit time of 0.75 s for a bolus made with 10 ml yoghurt and 5 g manganese ferrite (MnFe_2O_4) (giving a total volume of 11.3 ml). This gives a flow speed of around 0.05 m/s, assuming a diameter of 0.02 m for UES opening or 0.2 m/s assuming a diameter of 0.01 m. Very recently, Kumagai *et al.* (2009) reported that the maximum velocity of bolus flow showed a linear correlation to the log of bolus viscosity. They observed a maximum velocity of 0.6 m/s for water and a gradually decreasing velocity to around 0.1 m/s for viscosity boluses of CMC (carboxymethylcellulose), xanthan gum, guar gum and pregelatinised starch.

7.2.1.3 The oesophageal phase

The opening of upper oesophageal sphincter marks the beginning of the oesophageal phase of a swallowing process. The oesophagus is a tubular structure connecting the pharynx and the stomach and functions solely as bolus passageway. The bolus is pushed forward by a series of peristaltic waves due to sequential contraction actions starting from the superior constrictor of the pharynx, followed in turn by the middle and inferior constrictors and then by the striated muscles in the upper third of the oesophagus. When the contraction waves reach down to the smooth muscle of the lower third of the oesophagus, the lower oesophagus sphincter relaxes and allows the bolus to enter the stomach. The lower oesophagus sphincter is tensioned at rest to prevent regurgitation from the stomach and becomes relaxed only for bolus passing. It should also be noted that, throughout the swallowing process, the bolus is pumped and pushed as a result of muscle contractions, and therefore the influence of gravity is almost negligible to bolus flow.

Overall, swallowing is a complicated and dynamic sensorimotor activity, involving at least 26 pairs of muscles and 5 cranial nerves (Hiimeae, 2004). The oral phase is volitional, while the oesophageal phase is wholly governed by reflex control. The pharyngeal phase can be seen as semi-reflexive, triggered by the central pattern generator (CPG) in the brainstem (Mistry and Hamdy, 2008). Figure 7.2 shows sequential images of the swallowing of a liquid bolus. It is obvious from these images that, during swallowing, the bolus is deformed and stretched in order to squeeze through the narrow paths of oropharynx and

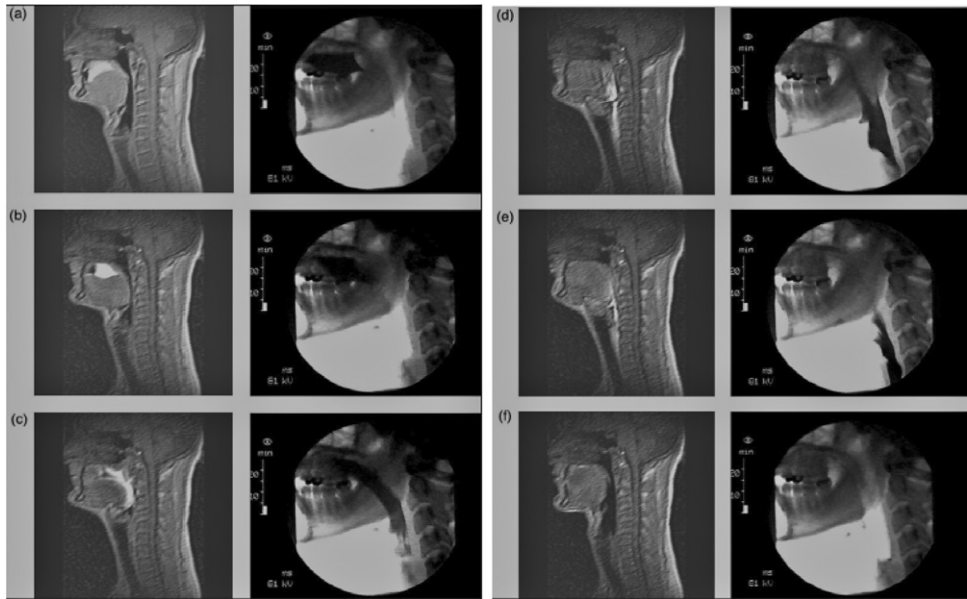


Figure 7.2 Six important oral and pharyngeal stages (a–f) of the swallowing of fluid contrast medium from real-time MRI (left side) and videofluoroscopy (right side) series: (a) bolus uptake, (b) beginning of bolus transport, (c) velopharyngeal closure, (d) triggering of the swallowing reflex, (e) propulsion of the bolus towards the oesophagus, and (f) original position with swallow breath. Reproduced from Buettner, *et al.*, 2001, with permission of Oxford University Press.

oesophagus. Figures 7.2a and 7.2b could be seen as the oral stage of a swallow, Figures 7.2c and 7.2d show bolus transition during the oropharyngeal stage, Figures 7.2e is an image of bolus flow towards the oesophagus, while Figure 7.2f is the image at rest after the bolus has been cleared from the whole tract. It appears that the bolus flow in the oesophageal phase is much smoother and slower than that in the pharyngeal phase. It has been reported that swallow-induced oesophagus peristalsis propagates at about 2–4 cm/s (Dodds, 1989). This means that it can take 5–10 seconds for a bolus to traverse the entire body of the oesophagus (about 20 cm in length) before entering the stomach.

7.2.2 Oral pressure and bolus swallowing

7.2.2.1 Bolus location before swallowing

Recent research shows that a food bolus spreads out much further than previously believed. Even though it is generally correct that the main body of a bolus remains within the oral cavity when a swallow is initiated, the head of the bolus reaches much further to the dorsum, or the back side, of the tongue surface. This is particularly true when a solid food is consumed. During eating of a solid food, particles have to be chewed to a proper size and mixed up with saliva. The mixture is then moved through stage II transportation to the back of the oral cavity. A bolus is then accumulated to an appropriate size (volume) before a swallowing action is triggered.

In consuming a liquid food, spillage or leakage of liquid into the valleculae is not unusual even in healthy subjects. Figure 7.3 is a fiberoptic endoscopic image of milk spillage into



Figure 7.3 Fibreoptic endoscopic imaging of diffuse spillage of milk into the vallecula and pyriform sinuses bilaterally before the onset of airway closure. Reproduced from Leder and Murray, 2008, with permission of Elsevier.

the valleculae and pyriform sinuses. The picture clearly shows that the spillage occurs while the airway (larynx) is still fully open. It is now generally accepted that bolus position before swallowing can vary significantly among individuals and even vary for the same subject when eating different foods. This variability is especially true when consuming a food that has both liquid and solid parts. The leading edge (liquid part) of the food often enters the hypopharynx while its solid part is still chewed in the oral cavity. Videofluoroscopic observation reveals that the vertical distance between the bolus head and the intersection of the tongue base and mandibular ramus varies hugely among individual subjects, between 47mm above and 35mm below the intersection, while causing neither penetration nor aspiration (Stephen *et al.*, 2005).

7.2.2.2 The oral pressure

Any fluid transportation requires an energy input and this is also true for bolus swallowing. The energy consumed in fluid transportation can be in different forms including potential energy, kinetic energy and pressure energy. For bolus transportation, pressure will be the dominating source of energy provision, through the contraction actions of the responsible muscles along the oral–pharynx–oesophagus tract. The pressure energy is essentially needed to overcome either the kinetic energy increase due to velocity gain or the energy loss due to friction. The exact profile and pattern of the pressure application within such a complicated system has not been properly investigated, but there is no doubt that a pressure increase by coordinated muscle contraction is needed at each stage of a swallowing process.

The very first push to a bolus flow is the pressure produced by the tongue pressing against the hard palate. This coincides with the triggering of a whole swallowing sequence.

This pressure is often referred to as the oral pressure and is generated initially by a close contact of the tongue with the anteriomedian part of the hard palate, then with the circumferential part, and finally softly with the posteriomedian part. Various efforts have been made to measure and map the oral pressure, but reported literature results are somewhat contradictory. In the literature, different terms have been used interchangeably, such as swallowing pressure, oral pressure, tongue pressure, stress and so on, even though their exact physical meanings are subtly different. A swallowing pressure is a general term that represents the minimum pressure required to swallow a bolus, though exactly at which location the pressure refers to still needs to be defined. An oral pressure represents the pressure created inside the oral cavity by the actions of the tongue pressing and muscle contractions. Tongue pressure is strictly speaking the pressure or the stress produced by the pressing of the tongue against the hard palate. Therefore, tongue pressure (or stress) is not necessarily the pressure experienced by the bolus, though a positive correlation between the two is usually expected. For the sake of convenience, the term oral pressure will be used in the following discussion.

Methodologies reported in the literature for oral pressure measurements were initially designed for different purposes and do not necessarily measure the same thing, though the same term of oral pressure was used. It is therefore not surprising to see a wide range of variation of reported results. Ferguson (2006) indicated that a pressure of up to 10 kPa can be generated in the midline of the tongue when the tip of the tongue thrusts against the anterior teeth. Ono *et al.* (2004) used a series of probes to measure tongue pressure on the hard palate during swallowing and observed a maximum of up to 25 kPa for healthy subjects. This result is supported by a very recent study: Abdul Wahab *et al.* (2011) used three-bulb manometry to measure anterior oral pressure, middle oral pressure and pharyngeal pressure. They observed a maximum of 150 mmHg (~20 kPa) for anterior glossopalatal pressure, 185 mmHg (~25 kPa) for mid glossopalatal pressure and between 92 and 111 mmHg (12 to 15 kPa) for pharyngeal pressure. However, Utanohara *et al.* (2008) found that tongue pressure could be much higher, reaching as high as over 50 kPa for healthy young adults. They also reported that ageing is the main reason for reduced capability in applying tongue pressure. Healthy subjects in their 70s have an average tongue pressure of 32 kPa, nearly a quarter lower than that of age groups in their 20s and 30s (Utanohara, *et al.*, 2008). (The decreased capability of applying tongue pressure no doubt has important implications to the eating and swallowing of elderly people.)

Another important factor in measuring oral pressure is the size of the probe. This is because the pressing area of the tongue against the hard palate varies throughout a swallowing process. The size of the probe will therefore have a direct influence on the calculation of the pressure if force is the primary physical parameter of measurement. It should also be noted that the exact probe location within the oral cavity is sometimes very difficult to repeat among measurements and among subjects and could be another important source of variation.

The magnitude and duration of the oral pressure were found to be significantly higher in the anteriomedian part and significantly smaller in the posteriomedian part (Ono, *et al.*, 2004). During the early stage of swallowing, the teeth are in centric occlusion and lips are brought together so that the oral cavity is firmly sealed anteriorly. Therefore, the pressure difference along the midline of the tongue causes backward flow to the bolus. It has also been reported that as the body of the tongue drops back from the palate, and the pharyngeal musculature relaxes, a negative pressure can be induced at the back of the mouth (Kennedy, *et al.*, 2010), effectively increasing the driving force for bolus flow.

The pressure drop from the oral cavity to the pharynx is probably for two reasons: to overcome friction energy loss of bolus flow and to gain bolus kinetic energy (increased velocity). Little has been reported on the pressure in the pharynx region during swallowing, but the pressure in this region is expected to be much smaller than that in the oral cavity, from around as low as few kPa (Ferguson, 2006) to as high as 15 kPa (Abdul Wahab *et al.*, 2011). Based on the consideration of energy consumption, a pressure of proper magnitude in the pharyngeal region is critically important for a smooth swallow. A too low pharyngeal pressure would create difficulties in pushing the bolus through the upper oesophagus sphincter, causing an incomplete swallow or a large amount of bolus residue in the pharynx. Residual food particles would easily leak into larynx causing coughing or even choking. On the other hand, a too high pharyngeal pressure is undesirable, since it would require a much higher oral pressure to initiate bolus flow and possibly lead to a turbulent flow or even food entering the nasal cavity.

7.2.2.3 Measurements of oral pressure

Despite various attempts reported in the literature, there has been no standard methodology for oral pressure measurements (Ono *et al.*, 2009). The main difficulties for reliable and reproducible oral pressure measurements are due to two aspects: the restrained access of the oral cavity and the irregularity of oral geometry. Insertion of a measurement probe inside the mouth causes discomfort and often leads to non-habitual oral movements. The geometry of the oral cavity varies significantly, making measurement even more difficult, not only among individuals but also within the same subject during the eating process. So far, manometer and sensing probes are probably the most commonly used approaches for oral pressure measurements. A small balloon type probe is normally inserted into a subject's oral cavity. The pressure exerted on the balloon after tongue pressing can be measured by either a gas or a liquid transducer mechanism (Shaker *et al.*, 1988). Such a measurement is easy to conduct and does not cause too much discomfort to the subject. But a major disadvantage is that it can only give a reading of an average pressure, not the pressure profile of the oral cavity. A much improved method was reported by Tsuga *et al.* (2003), who managed to link up three transducers to measure the pressure at three different locations inside the mouth (front, middle and back). The pressure transducer mechanism has also been applied by Medoff-Copper *et al.* (1993) in studying the sucking behaviour and sucking pressure of infant babies. They simply attached a liquid-filled transducer tube to the nipple of a milk bottle to monitor pressure changes during milk drinking. A positive correlation was observed between the sucking pressure and the amount of milk intake per unit of time. It was recommended that this pressure could be used to determine the hunger/satiety status of a baby (Medoff-Copper *et al.*, 1993).

Multiple-point sensor sheet is a recent development for oral pressure measurements. These sensor sheets are either based on a mechanical transducer mechanism (strain gauge) or an electrical transducer mechanism (resistance to an electrical current). The sensor sheet technique has unique advantages. Most sensor sheets are very thin allowing easy access to the oral cavity, highly flexible for easy adaptation to oral shape, and are capable of giving an instant digital reading. The technique has been proved to be feasible and reliable in measuring the profile of biting forces and biting pressure (Kohyama and Nishi, 1997). It has also been reported that, by applying sensor sheets, it is possible to map the pressure profile within the oral cavity during eating and swallowing (Ono *et al.*, 2004; Kennedy *et al.*, 2010). However, like most sensing probe techniques, a sensor sheet can only measure

the pressures or the stresses at the contacting points or the contacting areas between the pressing tongue and the palate. These may not necessarily be the true pressures of the bolus. Also, dental adhesive is normally used to secure the sensor sheet inside the mouth, but fixing a flat sheet to a curved surface means bending (or even folding) the sheet becomes inevitable and hence can lead to experimental errors.

7.3 THE FORMATION OF A FOOD BOLUS AND THE TRIGGERING CRITERIA OF BOLUS SWALLOWING

7.3.1 Dynamics of bolus formation

The preparation of a food bolus is a continuous process and requires involvement of chewing and size reduction, particle movements, saliva incorporation and other oral actions. Because of the involvement of multiple oral actions and its dynamic nature, bolus formation has never been identified as an independent step of eating sequence in various models of food oral management. In order to form a bolus, trituated food particles are mixed up with (and lubricated by) the saliva and are transferred and moved by the tongue to the back of the oral cavity. Whether a bolus of food particles is ready and suitable to be swallowed depends on a number of influencing factors including the particle size, the mechanical strength and deformability of food particles, the geometry of food particles, surface lubrication, saliva participation, surface tension of oral fluid and so on.

Hutchings and Lillford (1988) were probably the first to propose a simple physical model to explain the dynamic nature of bolus formation and the essential features of a ready-to-swallow bolus, by using three dimensions (degree of structure, degree of lubrication and time) (Figure 7.4). This model suggests that a proper food bolus has to have food particles

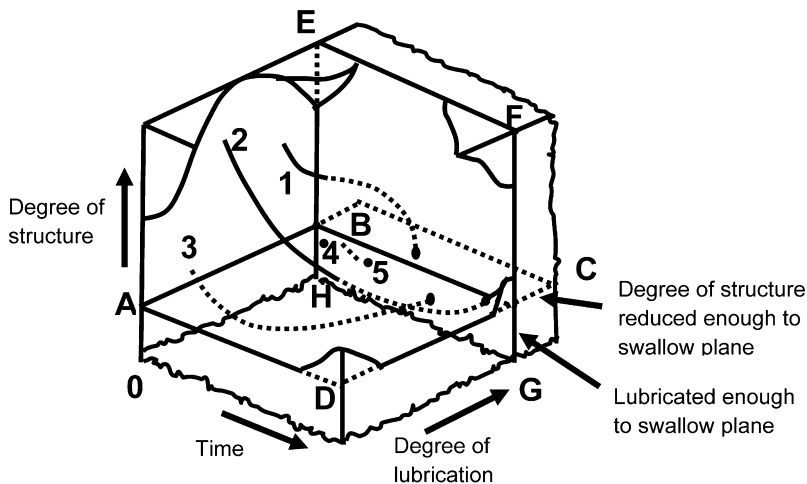


Figure 7.4 The 'mouth process model'. 1. Tender juicy steak; 2. tough dry meat; 3. dry sponge cake; 4. oyster; 5. liquids. Before a food may be swallowed, its 'degree of structure' must have been reduced below the level of plane ABCD, and its 'degree of lubrication' must have crossed plane EFGH. Adapted from Hutchings and Lillford, 1988, with permission of John Wiley & Sons.

that are small enough and have an appropriate amount of saliva incorporation and lubrication, both of which require a certain amount of oral processing time. Based on this assumption, the dynamics of bolus formation or the readiness of a bolus for swallowing could be quantified as a function of these parameters,

$$S = f(d, \phi, t) \quad (7.1)$$

where d represents the particle size, ϕ is the volume fraction of saliva, and t is time. Since both particle size and the amount of saliva is a function of oral processing time, therefore, the readiness of a bolus for swallowing can be simplified as a function of particle size, d , and saliva volume fraction, ϕ , or simply a function of oral processing time, t . This model has been widely referred in the literature as a description of the mechanisms of bolus formation and the determining criteria of swallowing. But unfortunately little experimental evidence has so far been obtained to support this model.

Prinz and Lucas (1997) proposed a very different model of bolus formation based on the colloidal forces acting on the food particles. They treated a food bolus as a cluster of particles held up together by the oral fluid and argued that a (sphere) food particle has two tendencies: to be attached to the oral surface or to be attracted together to form a cluster, depending on the balance of the two counter-acting forces: the adhesion force, F_A , and the viscous force, F_V .

$$F_A = 4\pi r\sigma, \quad (7.2)$$

$$F_V = \frac{3\pi\eta R^4}{64h^2t} \quad (7.3)$$

where r is the radius of the food particle, σ is the surface tension of the oral fluid, η is the viscosity of oral fluid, h is the distance between particles, R is the radius of the bolus and t is the time span of separation. The surface tension of the oral fluid tends to adhere particles to the oral surface, while the viscous force tends to drag particles to flow together (Figure 7.5). It was further recommended that the combination of the two forces gave an indication of the consistency or the cohesiveness of a bolus, F_C , and could be used as the determining factor in triggering a swallow:

$$F_C = F_V - F_A \quad (7.4)$$

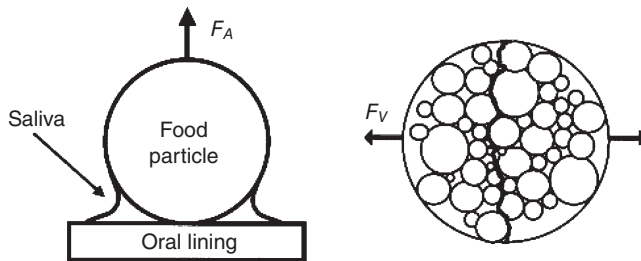


Figure 7.5 An illustration of the adhesion force, F_A , acting on a food particle due to surface tension and the viscous force, F_V , on the food bolus. Reproduced from Lucas *et al.*, 2002, with permission of Elsevier.

The feasibility of the model was tested using a numerical calculation method for boluses of Brazil nuts and carrot and it was suggested that boluses should be swallowed at their maximum consistency (Lucas *et al.*, 2002). However, the validity of the maximum consistency as the determining criterion in triggering a swallow remains questionable and has so far received no experimental confirmation from an independent study.

The above model may have a limited relevance to bolus formation in the early stages of an eating process. For example, during the first few chewing cycles of a dry food, there is a fast increase of the total surface area of food particles but a limited amount of saliva. Fractured food particles remain relatively dry and only become increasingly wetted when more saliva is secreted after continuous chewing. Surface wetting helps cluster formation of fractured particles and therefore the formation of a proper bolus. This dynamic process could be well explained by the theory of particle wetting and clustering proposed by Iveson *et al.* (2002). Their model indicates that, with a little liquid presence, a particle cluster is dominated by inter-particle friction. Such a cluster is difficult to deform and of course difficult to swallow. Under such a circumstance, particles will find it easier to adhere to oral surfaces than to stay together. This explains why the consumption of a powdery food is not as easy as it appears to be. High surface area and a limited amount of oral fluid are the causes of the difficulty. With increased saliva secretion, particles change their status from dry to partly wet and will be held together by the liquid bridge, exerting an adhesion force between connecting particles due to capillary and surface tension effects. Particle clusters can exist in either pendular or funicular status. The capillary force increases with the increasing liquid content until the capillary state is reached (see Figure 7.6). Once the liquid content exceeds saturation, viscous forces become important in holding particles together, a scenario discussed above in Lucas and Prinz's model. Figure 7.6 shows the changing status of a cluster of mono-distributed particles, from pendular to a droplet with the increasing presence of liquid. It was predicted that the tensile strength of a particle cluster of partial saturation would depend on a number of factors including the saturation status, particle size, granule porosity, surface tension of oral fluid, and the surface contact angle of food particles (Iveson, *et al.*, 2002).

7.3.2 Critical criteria in triggering a swallow

Even though every healthy individual knows perfectly well when to swallow, the criteria used to trigger a swallowing action remains a mystery. It is generally believed that both particle size and saliva secretion play a role in triggering a swallow. This has been proved by a very recent experiment conducted in the author's group. Healthy subjects were invited to consume various biscuits and the number of chewing cycles before swallowing was

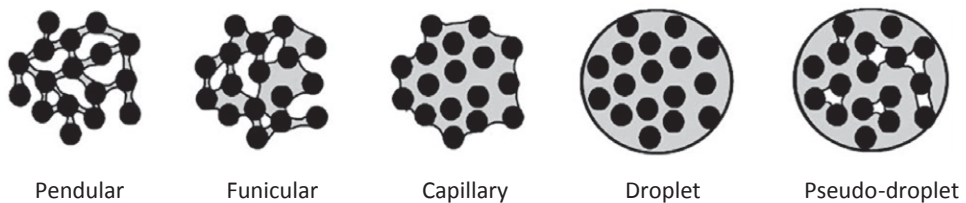


Figure 7.6 The different status of saturation of liquid-bound granules. Reproduced from Iveson *et al.*, 2004, with permission of Elsevier.

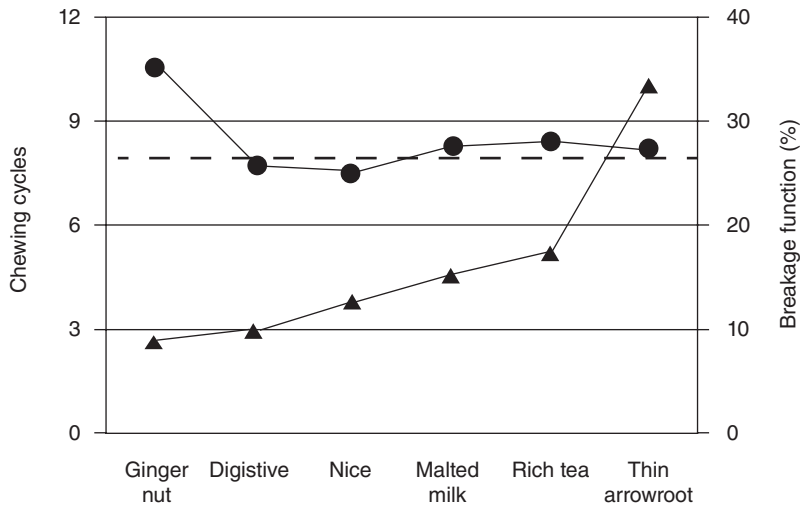


Figure 7.7 Correlation between breakage function and the number of chewing cycles for biscuits. The dashed line indicates a minimum of eight chewing cycles is needed to complete an eating process of highly fragile biscuits.

recorded for each subject and each biscuit. Mechanical properties of the biscuits were significantly different as characterised by their breakage function, a parameter representing the easiness of a biscuit breaking and fracturing (see Chapter 5). A biscuit with a large breakage function is easily fracture-able and requires less chewing action to obtain the required particle size. It was found that for biscuits, however fragile, a minimum of eight chewing cycles on average was needed before a swallowing action could be triggered. As shown in Figure 7.7, five of six chosen samples require the same number of minimal chewing cycles, despite significant differences in their breakage function. For example, the *Thin Arrowroot* biscuit has a breakage function of around 33%, more than three times of that of the *Digestive* biscuit (~10%). But the two biscuits showed no significant difference in the number of chewing cycles before a swallow was triggered. This observation suggests that, even though particles (of *Thin Arrowroot* biscuit) could have already reached the critical size, the bolus is still not ready to be swallowed, probably due to the shortage of saliva. The extended oral processing time may have little to do with particle size reduction, but is most likely to allow time for more saliva secretion so that biscuit particles can be properly wetted and clustered. This experiment shows that small particle size and an appropriate amount of saliva are both important determining factors for bolus formation and swallowing of a solid and semi-solid food.

The criteria used in triggering a swallow could be better considered from the view of optimum energy consumption or the minimal oral effort for swallowing. In fluid transportation, energy consumption is the most important determining factor. The essential principle is that energy consumed during transportation must be properly matched by the energy provision. This is also true for swallowing and bolus transportation, where the energy needed for bolus flow must be matched by the work of the oral device through combined contraction efforts of swallowing muscles. Since human individuals have limited muscle strength and limited capability in creating oral and pharyngeal pressure, one feasible hypothesis is that a food bolus should be easy to deform and flow so that it requires the

minimal oral effort (or a minimal amount of energy consumption) for transportation. The particle size reduction and saliva incorporation are probably the two oral actions needed to fulfil such a purpose. Based on this assumption, the theory of maximum consistency as the optimum point to trigger a swallow could be questionable. This is simply because of the fact that a food bolus at its maximum consistency will be most resistant to deform and flow and will require a much greater oral effort to swallow.

The hypothesis of minimal oral effort for bolus swallowing has also been tested by observing the oral residence time of various fluid foods. In theory, a fluid food requires no chewing and its swallowing could be a straightforward action. However, it was observed that a highly viscous food tends to stay longer in the mouth before being swallowed. A total of 28 fluid foods were tested and it was found that the total length of oral residence time appeared to have a positive correlation with the perceived difficulty of swallowing for these fluid foods (Figure 7.8, Chen and Lolivret, 2010). Further measurements of the shear viscosity and tensile stretch-ability of these fluid foods both showed positive correlations with the oral residence time, with the tensile stretch-ability giving a much higher correlation factor. One possible explanation of the extended oral stay is that it helps to produce more saliva and increase saliva incorporation into the food. This will inevitably increase the flow-ability of the bolus and make swallowing much easier. Taniguchi *et al.* (2008) investigated the swallow of some highly consistent foods and observed that the total swallowing time and oral ejection time were significantly longer for the food made of 1.5% agar powder

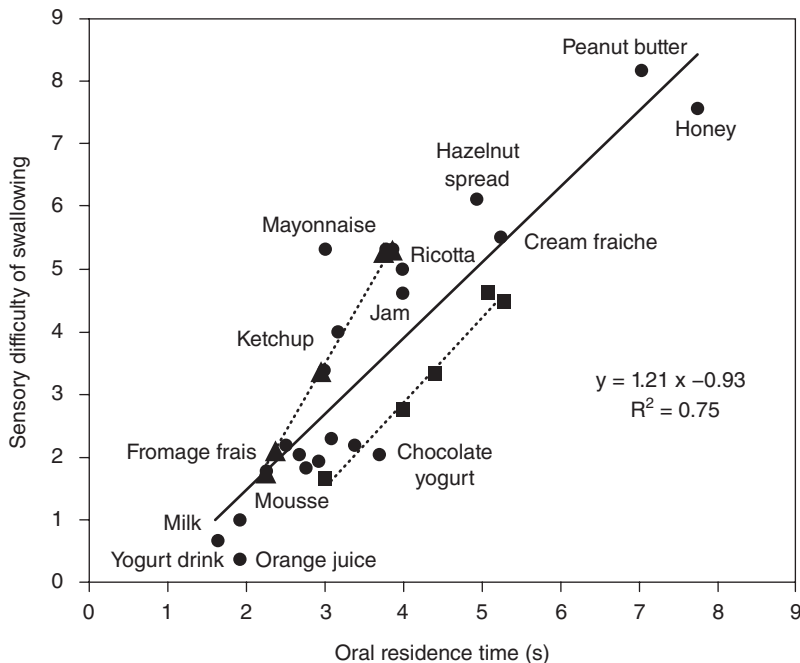


Figure 7.8 Correlations between the sensory difficulty of swallowing and the measured oral residence time. The solid line gives a regression of all tested food with a R^2 of 0.75. The two dashed lines are regression lines for the two sets of lab-constituted jelly (triangles) and custards (squares), with R^2 of 0.99 and 0.98 respectively. For reasons of legibility, only some of foods are marked in the graph. Reproduced from Chen and Lolivret, 2010, with permission of Elsevier.

than that for other less thick foods. They also observed that pharyngeal transit time and clearance time were significantly longer for a high viscosity material (syrup). Raut *et al.* (2001) demonstrated that increased bolus viscosity led to increased amplitude of the bolus wave and prolonged clearing contraction of the pharynx, with a slower propagation velocity in the oesophagus and a longer oral transit time. The prolonged oropharyngeal transit time for increased bolus consistency has also been positively confirmed by some other researchers (Steele and van Liesgiut, 2004; Troche *et al.*, 2008). All this evidence indicates that easy flow-ability is essential and could be the determining criterion in triggering a swallow. There has been no reported literature on the minimal flow-ability for bolus swallowing. However, it is reasonable to believe that such a value could be highly subject-dependent, depending on an individual's capability to create an oral pressure. As a rule, the swallowing pressure needed for a bolus to flow through the oropharyngeal system must be matched by the individual's capability in creating an appropriate oral pressure.

7.3.3 Influences of food properties on bolus formation

Particle size distribution, saliva incorporation and rheology are the three main factors that attract the most attention in studying bolus formation and swallowing (Engelen *et al.*, 2005). Since there is so far no feasible technique for *in situ* bolus studies, collection of bolus samples is a major technical challenge for such studies. Common practice is to ask subjects to chew a food sample and to spit bolus out when the subject feels ready to swallow. This process is highly subjective and judgemental. Therefore, a subtle difference between the collected bolus sample and the actually swallowed bolus should not be overlooked.

Peyron *et al.* (2004) studied particle size distribution of food boluses of six different foods (peanut, almond, pistachio, carrot, radish, cauliflower). They found that particle size distribution was highly food-dependent. For example, particles were found to be much larger in vegetable boluses than that in nut boluses, though similar size distribution patterns were noticed among nut boluses and among vegetables boluses. More surprisingly, they observed that there was little inter-individual variability among ten young healthy subjects in the particle size distribution for all six foods. This study was further extended to include a much wider range of foods, including gherkins, stoned green olives, mushrooms, egg white, ham, chicken breast, cheese and coconut (Jalabert-Malbos, *et al.*, 2007). Again significant particle size variations were observed only among foods, with much smaller variation among subjects. There appeared to be a correlation between the hardness of the food and the average particle size of its bolus. As a general trend, boluses of hard brittle food materials tend to have smaller particles, while soft deformable foods have boluses of much larger particles (Figure 7.9). At least two conclusions can be drawn from these studies: first, properties of the food play a very important role in bolus formation and swallowing; and second, the criteria used by these health individuals in triggering a swallowing action could be the same or very similar.

It has been recently noticed that boluses of different foods vary not only in particle size but also in the amount of incorporated saliva. It was observed that the amount of saliva was much higher in nut boluses than that in vegetable boluses. For example, a bolus of roasted peanuts contains on average $44 \pm 9\%$ saliva, a bolus of roasted macadamia contains on average $36 \pm 10\%$ saliva, but a bolus of raw carrot contains only $17 \pm 8\%$ saliva. The huge differences in saliva content between nut boluses and vegetable boluses may suggest that hard brittle nut particles are more difficult to swallow and therefore require more saliva to wet and cluster these particles. The marginally lower saliva content in a bolus of roasted

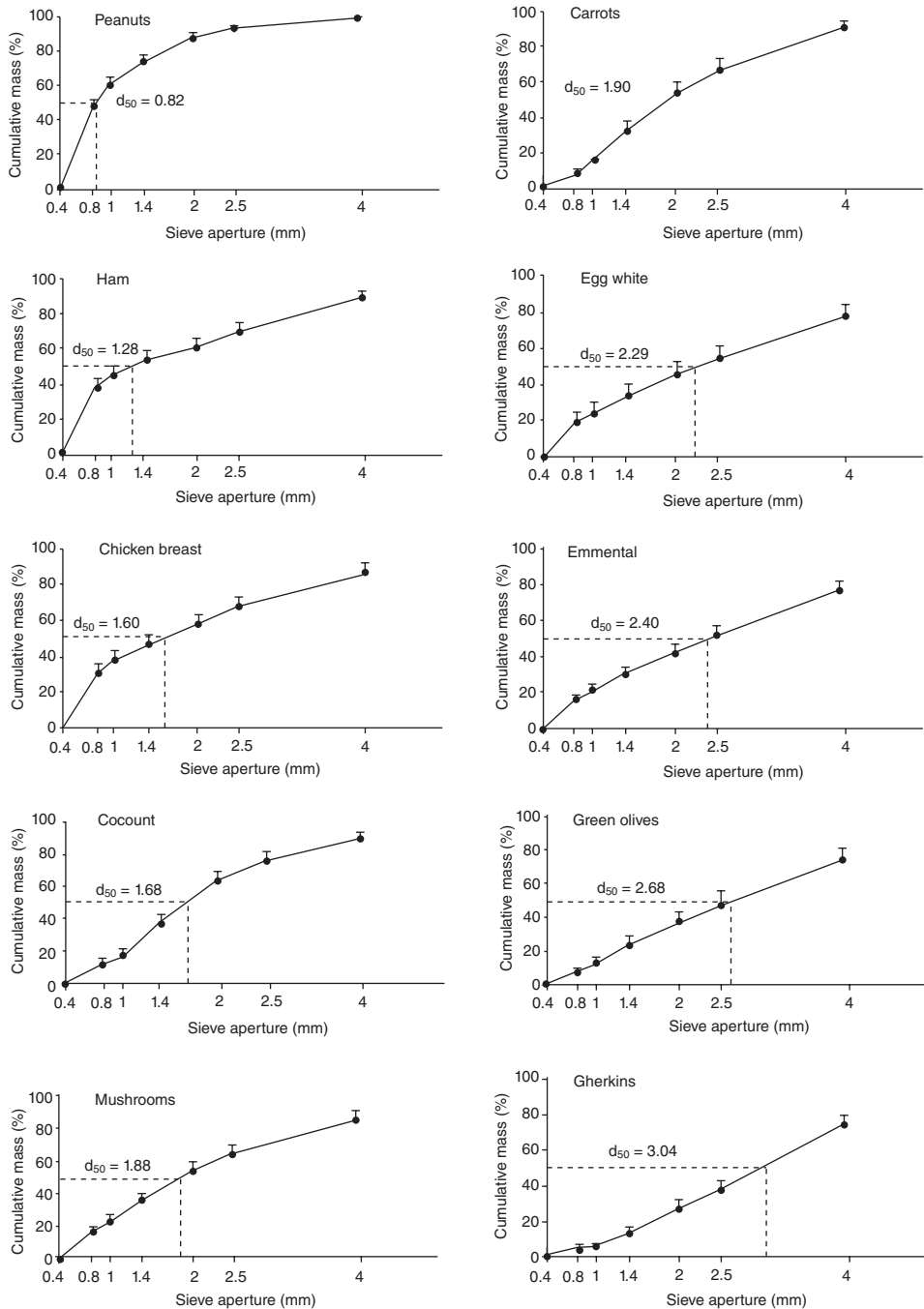


Figure 7.9 Particle size distribution profiles for 10 different food boluses. Means of the cumulative mass of particles are the percentage of the total mass of the food bolus recovered after mastication. The median particle size (d_{50}) of each food bolus is the calculated value based on weight. Reproduced from Jalabert-Malbos, *et al.*, 2007, with permission of Elsevier.

macadamia than that in roasted peanut bolus could be due to the fact that the macadamia is much more oily (69% fat in macadamia compared to 50% fat in peanuts). As indicated by Iveson *et al.* (2002), the surface of oily particles should have reduced wetting capability and a cluster of such particles will be much more flow-able and stretch-able. The significantly less saliva in a carrot bolus could be understandable for a juicy vegetable with relatively weaker mechanical strength.

The size of bolus (or the amount of food) has a strong effect on how a bolus is dealt with inside the oral cavity. It was reported that, to accommodate a larger amount of food or a larger bolus, a significant increase in the distance and range of chin movement was necessary during a chewing sequence (Blissett *et al.*, 2007). Wintergerst *et al.* (2008) examined the effects of bolus size (1, 2, 4 and 8 g of soft and hard gums) on the kinematics of chewing cycles and found that 2 g bolus size gave the least within-subject variability. This suggests that normal individuals are probably used to accommodate a certain amount of food for an eating process. Too large or too small bolus sizes may both lead to an irregular or non-habitual oral behaviour.

It is also very important to note that food transition and bolus formation is not simply a physical process of size reduction and saliva incorporation, but can also involve digestive disintegrations. The oral enzymatic degradation of cereal foods as a result of the digestive interactions of starch components with the α -amylase in the saliva could have a huge influence on bolus properties of such foods. Hoebler *et al.* (1998) indicated that during the short step of oral processing, about 50% of bread starch and 25% of pasta starch was hydrolysed and transformed into smaller molecular masses. This will lead to significant changes in the sensory texture (e.g. decreased viscosity and increased flow-ability) and sensory flavour (e.g. increased sweetness) of the food. This enzymatic effect on cereal boluses has been confirmed by Prinz *et al.* (2007) on the boluses of starch-based custards both *in vivo* and *in vitro* using a vane mixer to mimic oral processing. They observed a much faster viscosity decrease when the bolus was mixed with 0.1 ml saliva than when it was mixed with the same amount of water. Therefore, enzymatic disintegration must also be taken into consideration in the studies of bolus formation and swallowing of starch-containing foods.

7.4 CONCLUDING REMARKS

Swallowing is a complicated and highly coordinated oral action for bolus transportation from the oral cavity to the stomach. For convenience of description, a swallowing process can be divided into three phases according to the anatomy location of the bolus: the oral phase, pharyngeal phase and oesophageal phase, even though many studies have confirmed that bolus location is much more complicated and can occur across different regions simultaneously during swallowing. Oral pressure or the pressure drop along the bolus pathway is the main driving force for swallowing. The pressing of the tongue against the hard palate and the contraction of other swallowing muscles are the main sources of oral pressure creation. It is proposed that the swallowing pressure needed for a bolus to flow through the oropharyngeal system must be matched by the individual's capability in creating an appropriate oral pressure. Particle size distribution, saliva incorporation and surface wetting of food particles are the three most important factors influencing flow properties of a bolus, but no single one of these factors can be used independently as the determining criterion in triggering a swallow. It is the combination of these factors that determines the trigger

point of a swallowing action, even though the quantification and determination of such criteria requires further investigation.

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Part Three

Food Oral Processing and Sensory Perception

8 Oral Processing and Texture Perception

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8.1 INTRODUCTION

In this chapter we will discuss what texture is, why it is important for appreciation of food and how it is perceived. We will review some of the recent findings in the area of instrumental and sensory measurements and perception of texture, and how oral processing impacts on the texture of food and the perception thereof. The main part of the chapter will be based on research performed on semi-solids.

8.1.1 What is texture?

Texture is present all around us and it affects our choices and perceptions many times a day, in the clothes we wear, the furniture and textiles we choose, in the art we admire, not to mention the food we prefer. Texture has objective as well as subjective aspects: the soft skin of a baby is a sign of pureness and vulnerability, whereas the rough, weathered skin of an old sailor gives an impression of a lifetime of experiences. Although all aspects of texture are interesting, the focus of this chapter is food texture. All food has texture of some sort, ranging from tough to grainy and creamy, and texture is key to the appreciation and recognition of food.

In the literature, a number of definitions of texture can be found. One of the most used definitions for food texture was stated by Szczesniak (1963), who defined texture as ‘the sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces, the specific senses involved being vision, kinesthesia, and hearing’. Jowitt (1974) extended the definition of texture as follows: ‘the attribute of a substance resulting from a combination of physical properties and perceived by the senses of touch, sight, and hearing. Physical properties may include size, shape, number, nature and conformation of constituent structural elements’. Jowitt also stated that the appreciation of texture involves the subtle interaction between both motor and sensory components of the peripheral and the central nervous system. Even though most definitions given in literature differ slightly, all definitions agree implicitly or explicitly that texture is a multi-parameter attribute and not a single entity.

Texture of food can typically be described by numerous terms or attributes, such as thick, crunchy, soft or astringent, each referring to a specific textural property. As the definitions of texture above describe, food texture is sensed by the eyes, nose and ears, as well as by the hands during manipulation, even before the food enters the mouth. When the food has entered the mouth, intraoral attributes can either be sensed while the bulk of the bolus is still in the mouth and are then called mouthfeel attributes, or after the bulk of the food has been swallowed, and are then called afterfeel, or residual, attributes.

8.1.2 Why is texture important for the perception of foods?

Food is typically described by naive consumers in terms of taste and aroma, texture is frequently not mentioned. However, although consumers are often unaware of the importance of texture of food for appreciation, its importance is easily demonstrated by presenting them with samples of soggy cornflakes, wilted lettuce or stale potato chips. All of these examples are more or less unpalatable, although their chemical compositions remain much the same. Conversely, very good texture, such as a light and creamy mousse, is associated with excellent cooks.

Texture is a crucial criterion for sensory acceptance and rejection. Scott and Downey (2007) found that texture was one of the strongest driving forces in aversion of foods. The awareness of texture is often subconscious, where we expect a food to have a certain texture. If our expectations are met, then we focus more on the taste and aroma of the food. If however, the expectations of texture are breached, then the textural attributes become a reason to criticise and reject the food. For example, a few grains of sand in the spinach are a sufficient cause for rejection. Which textures are liked or disliked greatly depends on the specific food type. Generally, stringy, gummy or slimy foods are rejected, whereas crunchy, juicy or tender textures are preferred (Szczesniak, 2002). However, it is likely that such preferences or dislikes of raw oysters, for example, are also a function of our prior expectations and experiences for specific foods.

The notion of what an attractive texture is can also vary between cultures. While certain textures such as crispness seem to be universally liked, possibly through its association with freshness, other textures like sticky or slimy are found disgusting in some cultures while in other cultures they are highly appreciated. In addition, in some cultures consumers seem to be more aware of food texture than in others, as shown by the studies by Yoshikawa *et al.* in the 1970s, where Japanese students had a much richer texture vocabulary and were more sensitive to subtle variations in texture than American students (Yoshikawa *et al.*, 1970).

Texture is not only important for the appreciation, but also for the recognition of food. When foods are blended, resulting in a disappearance of important texture cues, correct identification based on remaining taste and aroma cues drops to 40% (Schiffman, 1977). Similarly, in an unpublished study, Engelen blended three different kinds of fruit and vegetable (white grapes, apple and lettuce) in order to destroy the structure of the food. Thereafter we asked 29 subjects to identify the three samples. This proved to be a more difficult task than we anticipated. Only half of the subjects identified the white grapes and the lettuce correctly. The white grapes were also identified as apple, cucumber, star fruit and gooseberry, whereas the lettuce was identified as diverse things as cabbage, beans, sugar snaps, carrots, cucumber, avocado, spinach and even grass. The apple proved to be the most difficult, with only 14% correct identifications. However, in this case the confusion seemed to be in the same direction, as most of the time the subjects confused the apple

with pear. These results highlight the importance of food texture in recognition as well as appreciation of food.

8.2 WHERE IS TEXTURE SENSED IN THE MOUTH?

Food texture and its importance to the consumer are considerably less well understood than factors such as aroma and taste (Kilcast and Eves, 1991). In contrast to taste, smell, vision or hearing we have no designated peripheral texture receptors *per se*. Oral contact with food can occur through the lips, tongue, palate, cheeks and teeth, all of which provide textural information. Texture sensations can range from slimy to rough, and from thick to crispy. The receptors involved in the diverse textural sensations can be found all over the oral cavity and include receptors for temperature, touch and irritant stimuli. The thermal receptors sense warm and cold stimuli. It is however not known exactly which receptors give rise to which tactile sensations, but one can make the conjecture that slowly adapting type I (SAI) receptors, which sense fine detail, are involved in the sensation of some aspects of texture, whereas rapidly adapting (RA) receptors are sensitive to slip and might be involved in sensations such as slimy or rough. During mastication of solid food, the texture of solid foods is largely perceived through periodontal receptors together with muscle spindles and Golgi tendon organs. These receptors transduce information on the forces and length of the masticatory muscles, in addition to the position of the mandible, and hence provide information on food characteristics such as a food's hardness, toughness and crunchiness during chewing. Free nerve endings of the trigeminal nerve are involved in the sensation of pungent chemicals such as piperine, capsaicin and the carbonation of fizzy drinks. Given the complex nature of texture, it is most likely that the perception of texture arises from the combined input from several types of receptors. Although receptors for sound are not present in the oral cavity, sounds arising from chewing and fracturing food are picked up by auditory receptors. See Chapter 2 (Engelen) for more details on the oral receptors, transduction and central processing.

8.2.1 The special case of the texture of fat

Some food preferences are considered innate, such as sweet and fat. From a biological point of view, animals including humans benefit when they recognise nutrients that are critical for survival before or at least during the first bite. Sweet taste signifies that the fruit is ripe, hence has the highest nutritional value, and fat is necessary both as an important means of energy as well as source of essential fatty acids. But how do we sense that we ingest sweet and fat before it reaches the digestive system? In the case of sweet, the lingual sweet taste receptors report instantly if the food that we are ingesting is sweet. In recent years, converging evidence from behavioural and physiological studies has arisen that suggests that fat (long chain fatty acids (LCFA) in specific) also exhibits gustatory cues (Khan and Besnard, 2009; Mattes, 2005; Chale-Rush *et al.*, 2007). However, smell and especially texture cues seem to be of large importance for the detection of fat. Fat may be even detected via the perceived temperature of the food (Prinz *et al.*, 2007). Rolls and his colleagues showed in 1999 (Rolls *et al.*, 1999) that neurons in the brains of macaque monkeys respond to the texture of fat in the mouth, particularly to liquid fat such as cream, independently of neurons clued in to smell or taste. Interestingly, the neurons responded just as much when the monkeys were fed silicone oil, which has a fat-like texture but no taste or smell, and no

nutritional value as fat. This response seems to be independent of viscosity (Verhagen *et al.*, 2003). Hence textural cues seem to be important for the oral recognition of fat.

8.3 TEXTURE VERSUS FOOD STRUCTURE

Texture is strongly linked to the structural state of foods, based on which foods can be categorised into three main groups, namely liquids, semi-solids and solids. The period between the point that the food enters the mouth and is swallowed, or oral residence time, is typically very short for liquids, longer for semi-solids and longest for solids. Liquid and most semi-solid foods can often be swallowed as such, but solid foods have first to be processed into a bolus that can safely pass through the pharynx and oesophagus to the stomach. Due to the longer oral residence time for solids, the consumer has more time to sense the different textural aspects of the food product. In addition, since most hard foods need to undergo significant chewing, much of the input we receive about the food's texture is derived from the jaw forces and the sounds created while chewing. However, particles and exuded liquids remaining after swallowing will also contribute to afterfeel sensations.

8.3.1 Liquids

Food and drinks ranging from water to full cream are considered liquids. The border between liquids and semi-solids seems to be rather fluid and a thin custard could be a liquid, while a thick one could be considered a semi-solid. One rule of thumb could be that the products that we drink are predominantly liquids, with the possible exception of smoothies and the like. As a result of us drinking liquids, the retention time in the mouth is usually very short and hence the texture of the liquid has to be assessed rapidly. What might be more important than the mouthfeel attributes in this case could be the afterfeel sensations. Wine is, however, an example of a liquid that is kept in the mouth for a long time by wine lovers, in order to extract all the sensations of the wine. The wine is swirled around in the mouth, the nasopharynx is opened to let as many odorants as possible through to the nasal cavity retronasally, and the tongue moves around in different ways. The texture of wine can be described in beautiful ways, such as astringent, the 'puckerish' quality of high tannin content, body, chewy, round and velvety.

8.3.2 Semi-solids

The category of semi-solids covers a large variety of different food products, including sauces, mayonnaise, many desserts, yoghurts, soft cheeses, as well as porridge and soft fruit. Most often these products are manipulated between the tongue and other oral parts, but require only little or no chewing. Even though retention time of semi-solids in the mouth is relatively short (up to 8 s) (Chen and Lolivret, 2011), mixing and reaction with and dilution by saliva are important for this group of foods. Especially for starch-based foods, the initial breakdown of starch by the salivary enzyme α -amylase affects the food and its perception (de Wijk *et al.*, 2004; Engelen *et al.*, 2003c). Many terms are used to describe the textural attributes of these products, among others thick/thin, melting, rough, creamy and sticky.

8.3.3 Solids

Solid foods include hard dry solid foods, such as crackers and breakfast cereals; hard solid foods such as carrots and some fruits; and solid wet foods such as meat. Crispy/crunchy; hard/firm; tenderness/ elasticity are all important textural attributes for solid foods, among others. Important processes taking place during the processing of these solid foods in the mouth are fracturing during the biting with the teeth and chewing with the molars, (rate of) water uptake, dissolving, lubrication, bolus formation, swallowing, and clearing (van Vliet *et al.*, 2009). To ensure safe swallowing, the food has to be broken down into particles sufficiently small to reduce the risk of aspiration. In addition, the bolus has to be relatively coherent, which takes place by wetting the bolus with a fluid, either by means of saliva, or oil or juice present in the product, released during chewing. In addition to the wetting effects of the fluids, they also lubricate the food bolus to allow for easy deglutition. The degree to which the product has to be broken down depends on its hardness and the fluid content in the product. In addition, the particle sizes will be larger for softer foods. Hence the time a bite of food stays in the mouth before swallowing depends on its hardness and water, or fluid, content. Consequently, hard, tough and/or dry foods stay in the mouth significantly longer than soft (semi-solid) or wet foods before swallowing. The main factors determining the readiness of food to be swallowed are fragmentation of the solid foods and their lubrication and aggregation to a food bolus as a function of time (Hutchings and Lillford, 1988; Prinz and Lucas, 1997; van Vliet *et al.*, 2009). Recent results by Chen and Lolivret (2011), proposed that the stretch-ability of a bolus is the key determining criterion in triggering deglutition (Chen and Lolivret, 2011).

8.3.3.1 Crispy and crunchy food

In recent years, the crispy/crunchy aspects of solid foods have been investigated with great enthusiasm. This is not surprising given the importance of a crispy or crunchy behaviour for recognition of fresh food. Zampini and Spence (2004) found that the perception of crispness and staleness of potato chips was affected by the sounds people hear when eating them. All crispy/crunchy foods are noisy (Vickers and Bourne, 1976) and consequently sound is one of the key sensory inputs for the perception of these attributes. This is also reflected in the vocabulary generated by trained panellists to describe crunchy; 'a combination of hardness and sound, mainly described as low-pitched', and crispy; 'a snap clean break, a light texture and a high-pitched sound' (Fillion and Kilcast, 2002). Courcoux and colleagues (2005) reported that the overall sound intensity level and the spectral profile of the sounds are two of the most important auditory factors influencing the perception of crispness. However, there is more to crispy and crunchy than noisiness. Both crispy and crunchy perceptions of food are directly related to the sound produced at fracture as well as to the mechanical and fracture properties of solid food materials, to their macro- and microstructure, and to the way they are eaten (Vincent, 1998). Varela *et al.* (2006) found that the sensory crispness of almonds could be predicted by combining acoustic and mechanical effects occurring during chewing, and that consumers were better able to discriminate between almond samples in terms of crispness by chewing than by biting (Varela *et al.*, 2008). The crispness/crunchiness can vary greatly from one product to another; for example, fresh fruits, nuts or extruded snacks all have a crispy/crunchy character, but based on very different causes as they are completely different in their structural features, composition and nature. High water content and high water activity will significantly change

the textural aspects of dry solid food (Primo-Martin *et al.*, 2008; van Nieuwenhuijzen *et al.*, 2008). This loss of crispness through hydration is a result of cell walls losing their stiffness when absorbing moisture (Vickers and Bourne, 1976).

8.4 THE MEASUREMENT OF ORAL PROCESSES

Oral processing in the mouth is the process by which food enters the mouth, is transported, manipulated, broken down in the mouth and swallowed. Understanding oral processing is necessary because these processes play a large role in food sensations. The measurements of oral processing focus either on the measurements of the oral movements themselves, or on their effects on the food.

Information on how food is processed in the mouth can be obtained either introspectively or instrumentally. Introspective measurements by Engelen and van Doorn (2000) involved asking subjects to describe chronologically, in their own words or by means of diagrams, what they did after placing the food in the mouth. The results indicated large individual differences in oral processing style. Four basic feeding styles for two semi-solid foods, custard and mayonnaise, were identified; simple (50%), taster (20%), manipulator (17%) and tonguer (13%). 'Simple' subjects placed the food on the front of the tongue, raised its tip to the palate to form a seal with the sides of the tongue against the teeth, then retracted the tongue and swallowed the food. 'Tasters' first moved the food backward in the simple manner described above, but additionally made a series of short sucking movements against the palate before swallowing. Sometimes 'tasters' described transporting the food via the cheeks to the back of the mouth. 'Manipulators' described a wide variety of behaviours, sometimes chewing with the incisors and allowing the food to flow into the buccal sulcus and/or chewing between the molars. 'Tonguers' made back and forth and sideways movements of the tongue against the palate. These results indicate that there is not one oral processing style, but that it varies greatly among subjects. Most likely we have all adopted an oral processing style which is optimised for us and balanced in terms of chewing efficiency and perception. The processing style is also dependent on the food we eat. Food that is ingested for its gourmet characteristics will most likely be kept in the mouth for a longer time and will be manipulated more intensely and variably to extract all the different flavours and sensations. Conversely, food that is ingested just to fill the stomach is ingested in a more effective way, probably stimulating fewer receptors.

Considerably more work has been done on the development of instrumental methods to study *in vivo* oral processing using a wide variety of techniques, ranging from observations of muscle activity (Van der Bilt *et al.*, 2001), jaw movement (Heath and Prinz, 1999), particle-size distribution (Lucas and Luke, 1983), the mixing of two colour chewing gums (Prinz, 1999), bite mark analysis of expectorated wax-wafers (Prinz and Lucas, 2001), facial movements (Mazari, 1998) and direct observation by video-fluorography (Palmer *et al.*, 1997). Most of this research has been focused on solid foods and resulted in the identification of the following steps: first the food is placed onto the anterior third of the tongue; second the tongue is elevated, compressing the food against the palate; third the tongue is depressed, transferring solid foods to the post-canine teeth; fourth comminution; fifth swallowing and sixth clearance. The passage of food through the mouth and food oral management have been described in detail by van der Bilt in Chapter 4. For semi-solids, oral processes are less well characterised, possibly because those processes require primarily tongue movements, which have proven difficult to monitor instrumentally without restrict-

ing masticatory movements. Attempts have been made to quantify tongue movements using video fluorography of lead markers glued to the tongue (Hiemae and Palmer, 2003). However, as only a limited number of markers can be used, the full complexity of the movements of the tongue is not captured and the radio-opacity of the mandible and teeth obscure the view of the tongue. Furthermore, x-rays have the disadvantage that the food must be mixed with a radio-opaque contrast medium, and exposure times must be kept to a minimum. Although potentially ideal, magnetic resonance imaging (MRI) is currently expensive and is too slow to resolve the rapid movements of the tongue made during oral processing.

A possible alternative is ultrasonic echo-sonography, extensively used in speech research (Green and Wang, 2003; Stone, 2005) and to a lesser extent in studies of dysphagia (Casas *et al.*, 2003). Initial results of application of echo-sonography to food research are promising; the measurements are non-invasive, but the resolution of the images is limited which makes interpretation difficult (de Wijk *et al.*, 2006b). More recently, articulography used in speech pathology, has been introduced in food research (Blissett *et al.*, 2007).

8.5 TEXTURE VERSUS ORAL PROCESSING

Food structure of solids and to a lesser extent of semi-solid foods is continuously evolving during oral processing, as indicated above. Different sensory attributes, including texture attributes, probably reflect food properties at various stages of the oral processing. In sensory research, food sensations are typically assessed by trained panellists under well-controlled laboratory conditions.

Anecdotally, the role of oral processes is easily demonstrated by expert tasters, such as wine tasters, who go through a series of specific elaborate movements in order to perceive small nuances in the wine percept. Somewhat more scientifically, this was explored further in the behaviour modification study, in which the role of oral movements in the perception of semi-solids was investigated (de Wijk *et al.*, 2003a). In this study, a set of five specific oral manipulations were defined and their effects on the perception of two types of semi-solids, vanilla custard desserts and mayonnaises were investigated. The oral manipulations ranged from simply placing the stimulus on the tip of the tongue to vigorously moving it around in the mouth. Most attributes showed a similar pattern, with the lowest attribute ratings where the tongue's movement was restricted and gradually increasing ratings with increasing complexity of the tongue movements. An individual's normal mastication behaviour, which exhibited the largest diversity and complexity of movements, typically resulted in the most intense sensations of flavour and mouthfeel (Figure 8.1). This suggests that consumers aim to maximise their food sensations. As a result thereof, foods that are not liked should result in mastication behaviours aimed to minimise food sensations. Results also indicate that the sensation of virtually all flavour and mouthfeel attributes requires at least some tongue movement. These manipulations mix food with saliva and thereby enhance mechanical and chemical breakdown, as well as position the food relative to the sense organs. The attributes least affected by tongue movements were typically those rated soonest after ingestion, in other words those that require no or only a few tongue movements to assess. The specific tongue movements required by the mouthfeel attributes provide information on the underlying mechanisms. It was suggested that simple up/down movements on the tongue are primarily used to assess the thickness of the food, whereas up/down movements in combination with horizontal movements along the palate are

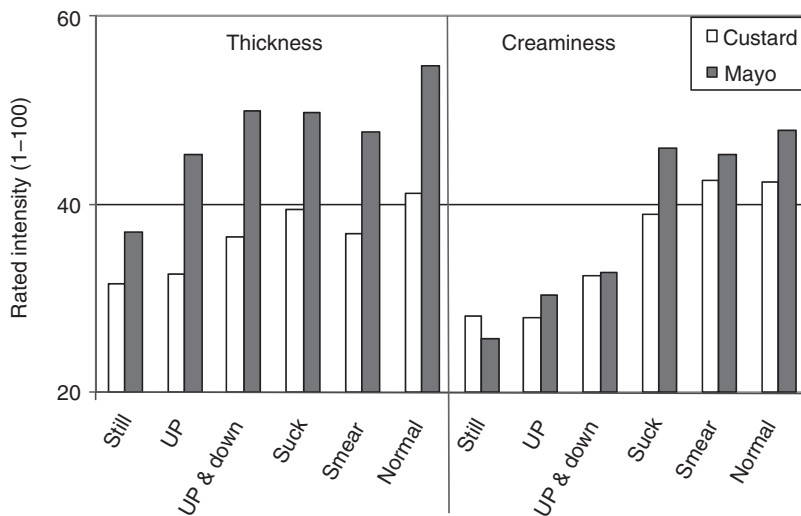


Figure 8.1 Ratings of perceived thickness and creaminess for mayonnaises (black bars) and custards (unfilled bars) per modified behaviour.

primarily used to assess sensations such as creaminess (de Wijk *et al.*, 2003a). The tongue is not alone in importance for the perception of the attributes. When texture attributes were rated with and without palatal coverage, the intensity of some attributes decreased with palatal coverage, while others remained unaffected (unpubl. obs.). Kremer *et al.* (2007) found that elderly people with dentures rated the food less creamy than the subjects without dentures and suggest that palatal coverage interferes with oral perception. Most likely the use of the entire mouth results in the strongest intensity.

Other studies in which oral movements were either measured directly with ultrasound (de Wijk *et al.*, 2006b) or indirectly by vibromyography (de Wijk *et al.*, 2008) verified that ratings of specific attributes are associated with specific oral movements. The results suggest that the subjects adopt specific oral movements to enhance specific sensations, not unlike wine tasters.

More complex movements should require more time to perform than simpler ones, which implies that sensations associated with more complex movements should take more time to assess than those associated with simpler movements. This hypothesis was confirmed by results of a reaction time study, which showed a difference of more than one second between the detections of sensations associated with simple and complex movements (de Wijk *et al.*, unpubl. obs.). Other evidence was provided by the complexity of oral movements and the chronological order in which sensations were perceived by a trained panel. Sensory panels typically develop their own vocabulary with respect to food sensations, and order these sensations chronologically. To verify whether this chronological order is determined by the complexity of their oral movements, we related the chronological order of sensations to the degree to which they benefit from complex behaviours, as determined in the behaviour modification study described previously (de Wijk *et al.*, 2003a). The results indicated that sensations that are perceived relatively early during oral processing, such as thickness, benefited less from complex movements, whereas sensations that

are perceived relatively late benefited most from complex movements. The only exception was the prickling sensation that was perceived late and was not affected by complex oral movements. This was explained by assuming that prickling required activation of trigeminal receptors, of which some are known to react relatively slowly. Further analysis of the combined results of the studies indicated that sensations that require simpler processing primarily reflect bulk properties of the oral food bolus, whereas those that require more complex movement reflect bulk and/or surface properties.

The role of oral movements in food perception may even extend to post-ingestive sensations of satiety or fullness. A number of recent studies have demonstrated that the degree of fullness, or satiation, elicited by a food is inversely related to the degree of oral processing. For example, Zijlstra *et al.* (2009) demonstrated that an increase in oral processing time from 3 to 9 seconds resulted in a reduction of up to 19% in *ad libitum* consumption of a custard to reach the same degree of fullness. More generally, eating slowly seems to result in increased satiety and lower consumption, and this has been verified by demonstrating increased levels of gut hormones Peptide YY and Glucagon-like Peptide-1 (Kokkinos *et al.*, 2010).

8.6 TEXTURE ATTRIBUTES ARE SYSTEMATICALLY RELATED

The combined percept of test foods – or sensory profiles – typically includes aroma, taste, trigeminal and texture mouth and afterfeel sensations. These profiles are often represented in an attribute space that graphically depicts the relationships between the various attributes themselves, as well as their relationships with products and possibly with the ingredients and instrumental measures (e.g. principle component analysis – or PCA – bi-plot). For example, the PCA in Figure 8.2 shows the combined results of sensory attributes for a series of starch-based custard desserts that differed in fat content, starch content and starch type (de Wijk *et al.*, 2006a). The results can be summarised by three main sensory dimensions. The first dimension runs from roughness to creaminess sensations and is primarily related to fat content. The second dimension runs from melting to thickness and is primarily related to starch content, whereas the third dimension running from airiness to heterogeneity is primarily related to starch type. The third dimension found in the study is probably directly related to the starch types used, which elicit grainy and heterogeneous texture sensations. Hence, the results demonstrate systematic relationships between sensory attributes and ingredients, at least for the type of product (custard desserts) used in that study.

The sensory space for the same custard desserts products was related to novel and standard instrumental tests to verify systematic relationships. The tests were developed to investigate bulk- and surface-related properties of foods before and after processing in the mouth. The results indicate a clear separation between tests reflecting primarily surface properties (Infra-red reflectance (IRR), friction and images) and those reflecting primarily bulk properties (rheological tests and turbidity), between tests reflecting fat related properties (friction, IRR turbidity), tests reflecting viscosity-related properties (rheological tests and turbidity), and tests reflecting properties related to starch-type (specific rheological tests and turbidity). The strong relationship between instrumental and sensory test was also demonstrated by the fact that the sensory ratings for most attributes could be successfully predicted from a combination of instrumental test results (de Wijk *et al.*, 2006a). In addition, the strong relationships provide insight into possible mechanisms underlying the sensory dimensions described above. The rough/creamy dimension seems to be related to

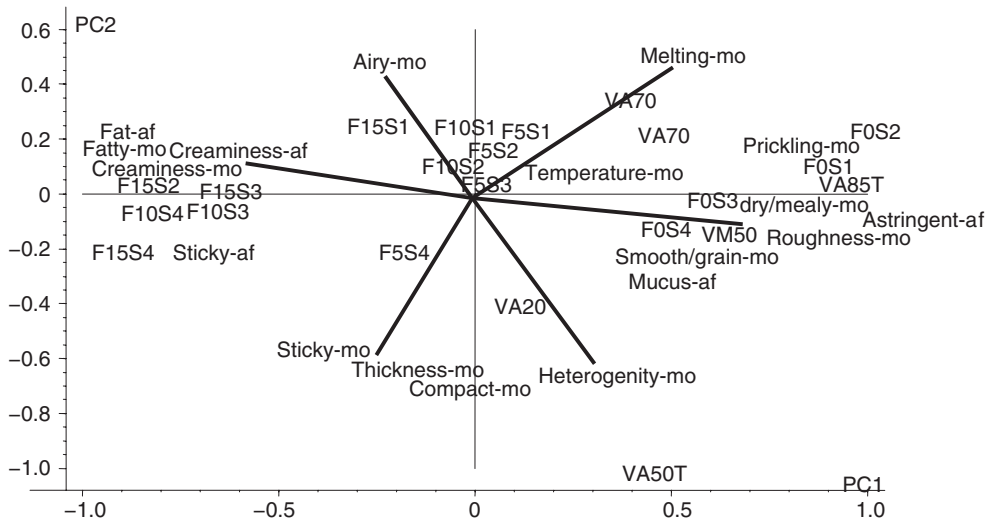


Figure 8.2 Principal component analysis of sensory mouthfeel (-mo) and afterfeel (-af) attributes. The bi-plot of PC1 versus 2 also depicts the samples with different fat levels (F0–F15), starch levels (S1–S4) and starch types (VA20, etc.). The three principal components explain 38% and 27% of the variance, respectively. Thick solid lines indicate the rough–creamy, melting–thick, and airy–heterogeneous sensory dimensions. Reproduced from *Food Hydrocolloids* **20**:1, de Wijk *et al.*, 2006, ‘Explaining perceived oral texture of starch-based custard desserts from standard and novel instrumental tests’. With permission from Elsevier.

the (lack of) lubrication between the food and the oral tissue. Attributes on the rough side of the dimension are associated with low fat content and high instrumental friction, whereas those on the creamy side are associated with higher fat content and lower instrumental friction. The thick/melting dimension seems to be closely related to stimulus viscosity. In addition, thickness ratings seem to primarily reflect properties of the bulk of the food bolus, whereas melting ratings reflect properties of the surface of the same bolus. In contrast, the airy/heterogeneity dimension seems to lack any apparent organisation; airiness is primarily associated with fat content and surface properties, whereas heterogeneity seems to reflect bulk properties. Subsequent research indicated that ‘bulk dominated’ sensations reflect the relatively intact food bolus whereas ‘surface dominated’ attributes reflect the properties of the broken-down bolus. The combined results of our studies indicate that sensations related to ‘bulk and surface’ properties are detected relatively quickly, and are associated with intense oral processing, whereas sensations related to surface properties are detected relatively slowly and are associated with less intense oral processing (de Wijk *et al.*, 2011).

8.7 THE ROLE OF SALIVA IN TEXTURE PERCEPTION

Saliva is expected to be of importance for the perception of food stimuli in the mouth. It can play a role through initial breakdown of food, (Engelen *et al.*, 2003a) (Young and Schneyer, 1981) by affecting flavour release (Hector and Linden, 1999), dilution of flavours

and tastes (Ruth *et al.*, 1996), precipitation of proteins by tannins, for example resulting in a sensation of astringency (Noble, 1995), lubrication of the oral tissue (Tabak *et al.*, 1982) facilitating manipulation of food in the oral cavity, formation of a swallowable bolus, and by transport of taste compounds to the taste buds. These examples indicate the value of saliva for the processing, appreciation and acceptance of food. Semi-solids are a group of products masticated without chewing. Therefore, mixing with saliva, including structure breakdown and dilution, is considered to be of relatively large importance in mastication of these products. Saliva consists of more than 99% water and contains a large number of organic and inorganic constituents, and the components of saliva are suggested to play a considerable role in mastication and perception. It is well known that there are large variations in the composition of saliva originating from different glands and different subjects (Veerman *et al.*, 1996), but it is not known how these variations in salivary characteristics affect sensory ratings. It seems plausible that both the volume and composition of saliva present in the mouth while eating are of importance. For more information on saliva and oral processes, please refer to Chapter 3 (Carpenter). To elucidate the role of saliva in texture perception, we designed a series of studies in our lab.

8.7.1 Saliva flow rate and texture perception

In the first study we established salivary flow rates at rest and after chewing, smelling odours and tasting citric acid (Engelen *et al.*, 2003c). The highest flow rate was elicited by tasting, followed by chewing and smelling, while the lowest flow rate was observed at rest. In order to investigate if and how the amount of saliva a subject produces has an influence on the sensory ratings, the four types of salivary flow rates were correlated with sensory ratings of vanilla custard dessert. No significant correlation could be found between any of the salivary flow rates and the sensory ratings. A subject with a larger volume of saliva in the mouth during eating did not rate the foods differently from a subject with less saliva present. The same pattern was seen for all types of stimulation. This finding could indicate that subjects are used to their own volumes of saliva and their ratings are compared with an internal standard to such a degree that the differences in sensory ratings between subjects cannot be explained by the inter-individual difference in saliva flow rate.

The continuation of the above study was to add extra saliva to increase the normal level that the subjects were used to (Engelen *et al.*, 2003a). Different fluid components of saliva were compared: in addition to saliva, water and an α -amylase solution were added to semi-solid and solid foods immediately prior to ingestion. The results indicate that many effects of saliva on flavour and texture sensations are attributed to dilution of semi-solids, since the three fluids produced similar results. For attributes concerned with thickness and melting of the product, however, saliva and α -amylase were more potent. Addition of saliva produced the strongest sensation for melting, indicating that saliva exhibits additional effects on the food.

We also observed significant effects of adding a fluid to solid foods (melba toast, cake, peanuts, cheese and carrots) for a number of attributes (Pereira *et al.*, 2006). Melba toast had the largest number of attributes that were significantly affected by adding the fluid. Subjects scored attributes related to drying, sound and hardness much lower after fluid had been added to the melba toast. Melba toast contains a very low percentage of water. Due to the additional fluid, melba is apparently softened much faster causing lower scores for both hardness and sound. Cake, a dry food, also scored significantly lower on the attribute drying, while after fluid was added, cake was perceived as less sticky and tough.

Peanut scored much lower on gooey, where the added fluid made it less pulpy during chewing. The sensory ratings of cheese were hardly influenced by the fluids, and the only attribute affected by added fluids was bite force. As cheese already has a high percentage of fat (31%) and water (35%), any additional water seems to play an irrelevant role. The perception of carrot remained unchanged, which is probably a reflection of the fact that carrot has a large percentage (90%) of water and carrot particles do not easily mix with water.

8.7.2 Saliva composition and texture perception

From the many components in saliva other than water that could affect the food while in the mouth, we selected three types for further study: proteins, mucins and α -amylase (Engelen *et al.*, 2007). In addition, the buffer capacity of the saliva was measured, as it is thought to be of importance for taste perception and pH dependent reactions. Proteins play a possible role in taste chemoreception and in the perception of astringency, viscosity and other mouthfeel attributes (Guinard and Mazzucchelli, 1996). The mucin analysed was the MUC5B, also known as MG1. MUC5B is a very large mucosal glycoprotein present in the mucous layer that covers and protects the oral cavity (Nieuw Amerongen *et al.*, 1995). The mucins exhibit diverse functions in saliva, among others these include protection against pathogens (Gibbons, 1979) and dehydration (Tabak *et al.*, 1982), and perhaps more important in this study, lubrication (van der Reijden *et al.*, 1993). α -amylase initiates starch digestion in the mouth. By cutting the long carbohydrate strands at the alpha (1–4) binding between glucose residues, the starch is reduced in its ability to bind water and the result is a lower viscosity of the product. Sensorially, α -amylase is shown to influence the sensation of melting in semi-solids (Engelen *et al.*, 2003a). Saliva acts as a buffering system (Larsen *et al.*, 1999), affecting the degree to which we perceive sourness (Christensen *et al.*, 1987). The buffering effect of saliva is attributed largely to bicarbonate/carbonate ions, and to a lesser extent to phosphate ions and proteins present in saliva (Bardow *et al.*, 2000), neutralising acids ingested or produced by microorganisms in the mouth. In this study we investigated the variation of salivary components after different stimulations; and the influence of salivary composition on flavour and texture sensations in custard and mayonnaise. The results showed that high α -amylase activity was correlated with a reduced sensation of vanilla flavour. A possible explanation is that due to instant enzymatic breakdown the custard was less viscous, resulting in a change in surface area and hence in reduced flavour release (Odake *et al.*, 1998). Perceived thickness was lower in subjects with high α -amylase activities for the starch-based custard. This observation was expected, since α -amylase breaks the starch down, lowering the viscosity, and there have been a number of studies showing that there is a strong relation between instrumental viscosity and perceived thickness (de Wijk *et al.*, 2003c). Slippery lip-tooth feel was stronger in subjects with low α -amylase activities. Conceivably the same mechanism is at work as for protein concentration. High individual α -amylase activity also decreased creamy afterfeel in both custard and mayonnaise. One possible explanation for this is that the creamy afterfeel is derived from a coating consisting of a layer of starch particles attached to mucosa. As α -amylase hydrolyses starch, breaking down the long starch strands into smaller units, high enzyme activity breaks down starch faster and more efficiently while the product is still in the oral cavity. Consequently, this could reduce the amount of starch left available to form a coating. Possibly, this results in a thinner coating, if any. Probably not only the quality of the coating is of importance for the perception, but also the thickness. A conjecture is that a thicker

coating results in a stronger creamy sensation. The reduced creamy sensation could also be related to the reduced flavour release (de Wijk *et al.*, 2003b).

8.7.3 Salivary enzymes and texture perception

As observed in the above study, the level of α -amylase was correlated to several sensory attributes. Amylase will be most effective in starch breakdown when it is mixed properly into the food bolus via tongue movements. As previously discussed, normal unrestricted oral processing of semi-solids typically results in the most intense sensations, whereas restricting a subject's processing behaviour results in less intense sensations (de Wijk *et al.*, 2003a). These results were explained by increased breakdown by α -amylase and shear forces during unrestricted processing. The role of salivary amylase in modifying texture sensations was further evaluated in studies in which the level of α -amylase activity was varied within subjects rather than between subjects (as in our previous studies). α -amylase was added in various concentrations to starch and carboxy methylcellulose (CMC)-based vanilla custard desserts (de Wijk *et al.*, 2004). Additionally, α -amylase activity was inhibited to various degrees by adding the pharmaceutical amylase inhibitor acarbose in various concentrations to the same test foods, just prior to ingestion. For starch-based custards, α -amylase resulted in increased melting and decreased thickness sensations, whereas acarbose had the opposite effect, that is decreased melting and increased thickness. Other attributes were affected as well. Creamy mouthfeel decreased with amylase and increased with acarbose. Similar results were found for creamy afterfeel (but only with acarbose) and fatty afterfeel (both amylase and acarbose). Creamy mouthfeel, which is considered to be a highly desirable food quality, decreased by up to 25% when amylase was added and increased by up to 59% when acarbose was added. Boosting desirable qualities of starch-based foods by reducing enzymatic breakdown instead of, for example, increasing fat levels is of potential interest to the food industry. These amylase and acarbose results demonstrate the importance of starch breakdown, particularly for sensations related to food viscosity. Since semi-solids are usually only kept for a few seconds in the mouth while eating, it has long been the assumption that this time frame is too short for α -amylase to have a significant effect on starch breakdown in the mouth. However, the above studies challenge this assumption. To further test the dependency of starch breakdown on these large changes in sensations, we compared starch-based custards with non-starch CMC-based custard. There were hardly any noticeable sensory changes in the CMC-based custard. This indicates that the effects of adding acarbose and α -amylase were indeed related to starch breakdown (de Wijk *et al.*, 2004).

8.8 ORAL TEMPERATURE AND TEXTURE PERCEPTION

Humans have a strong preference for the temperature of the products we consume (Lester and Kramer, 1991). Different foods have diverse preferred intake temperatures; ice cream is considered most pleasant when eaten cold and French fries taste the best when warm.

Under normal conditions, when we have our mouths closed and breathe through the nose, when the ambient temperature is not too extreme and when we do not have a fever, the oral temperature is about 35 °C. This changes when we eat or drink something hot or cold. Oral parts can be heated and cooled down depending on the temperature of the food.

An abnormally high or low oral temperature after consumption of hot or cold food quickly returns to normal oral temperature as a result of the richly vascularised mouth. It is well known that the physical chemical properties of food change with temperature, where for instance, an increase in product temperature changes the viscosity, causes melting of fats and enhances flavour and odour release. These processes also take place in the mouth, where ice-cream melts on the tongue and hot drinks are cooled down before swallowed, which minimises the damage to inner gastrointestinal organs and processes. These changes in properties of the food are likely to influence the texture perception. The sensation of temperature in the mouth has been discussed in Chapter 2 on oral receptors. However, in this section, we will discuss how temperature affects perception of food. It is interesting to see what happens to the oral temperature when in contact with hot or cold fluids and how this residual oral temperature affects sensory perception. Previous studies have shown that temperature itself can evoke a taste sensation (Cruz and Green, 2000) and that temperature can modulate other sensations such as the perceived hotness of capsaicin; the coolness of menthol; touch, where apparent roughness declined as skin temperature fell below, and was enhanced as skin temperature rose above, the baseline (Green *et al.*, 1979); and irritation, where heating has been related to increased irritation (Green, 1991), and cooling to decreased irritation (Stevens and Lawless, 1988).

In our lab, we examined the effect of various combinations of oral and product temperature on the perception of texture and flavour attributes (Engelen *et al.*, 2003b). By rinsing the mouth with water of different temperatures (10, 35 and 55 °C), the resulting oral temperatures were 27, 35 and 43 °C, respectively. Directly following the mouth rinse, a group of subjects assessed texture and flavour attributes of semi-solids at 10, 22 and 35 °C. Results showed that modulation of product and oral temperature had significant effects on a number of attributes. Not surprisingly, flavour intensities, melting mouthfeel and fat afterfeel increased, while subjective thickness decreased with increasing product temperature. Oral temperature also affected a number of mouthfeel attributes, such as melting and heterogeneity, where a high oral temperature increased both perceptions. A possible explanation could be an increased enzymatic action, leading to more structure breakdown. The high temperature itself could cause a change in viscosity of the stimulus in the mouth and hence a more melting sensation. This decrease in viscosity at the surface of the stimulus, in comparison with the bulk, could lead to a heterogeneous sensation when advancing the tongue through the stimulus.

We can therefore conclude that product and oral temperature influence the perception of certain flavour and texture attributes in semi-solids. For the evaluation of food, it is therefore important to consider if the food is going to be eaten in combination with, for example a hot or a cold drink, as this might influence the perception of the product. The fact that variation of product and/or oral temperatures highlights specific flavour/texture sensations may be useful for product development or quality control where one typically wants to focus on certain sensations and ignore others.

8.9 CONCLUDING REMARKS

In the present chapter we have endeavoured to give an overview of what oral texture is, how it is perceived and how texture perception is related to the oral processing taking place during feeding. Food sensations reflect various stages of oral food processing. For semi-solid foods, certain sensations such as thickness reflect the bulk properties of the food bolus

in the early stages of oral processing when the food is relatively intact. Sensing these properties requires relatively little time and simple tongue movements. Other sensations, such as creaminess and melting, reflect bulk as well as surface properties after considerable oral processing when the food is relatively degraded. Sensing these properties requires more time, and more complex movements. Oral processes also play an important role in the generation of aroma and taste sensations. Oral processes may not only affect sensations prior to swallowing, but may also affect sensations after swallowing. Normal processing probably comprises all types of movements required for the optimal perception of food sensations. The observed variations in salivary flow rates and components were partly reflected in sensory texture perception in semi-solids. The absence of prominent relationships between individual salivary characteristics and sensory ratings may be explained by the hypothesis that all subjects have their own references and are apparently used to their idiosyncratic salivary flow and chemistry. As a result, sensory ratings are relative rather than absolute, which results in the absence of between-subject differences. Product and oral temperature have been demonstrated to influence the perception of certain flavour and texture attributes in semi-solids.

In conclusion, given its important role in texture perception, it is advisable to include measurements of oral processing in texture studies.

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9 Oral Processing and Flavour Sensing Mechanisms

Sarah Adams and Andrew J. Taylor

9.1 INTRODUCTION

When placed in the mouth, food materials are processed and their physical state is changed. Typical physical changes include melting (ice cream), solubilisation (sugar candies), dilution with saliva (liquid drinks) or *phase* inversion of fat-continuous foods (butter and chocolate). As a consequence, the properties of the material that come into contact with the flavour sensors in mouth are often very different from that of the product as it enters the mouth. There are also changes with time as oral processing continues, for instance food is broken down by chewing or tongue-to-palate compressions and size reduction is a time-dependent process (see Chapter 4). When food is mixed with saliva, dilution can cause changes in pH and tastant concentrations or changes in the physical state of the food such as dispersion or, sometimes, aggregation into a bolus. Saliva also plays a role in the phase inversion of fat-continuous foods during mastication as the mechanical mixing creates new interfaces in the food product, which are then stabilised by the salivary proteins. The salivary enzymes present can also begin the breakdown process of some foods. After swallowing the food, a coating of food material is left behind in the mouth (and throat) leading to the perception of aftertaste and afterfeel. Throughout the whole process, the food material is interacting with the sensors in the mouth, throat and nose which feed information to the brain about the quality of the food, allowing the consumer to evaluate the product before swallowing. The main senses stimulated by oral processing of foods are:

- taste
- smell (aroma)
- touch (texture).

Temperature and trigeminal stimulation also play a role but these will not be discussed in detail here. The senses are integrated by the brain to give the consumer an overall impression of the food. Physical scientists, however, are more interested in understanding the structures, processes and chemicals that are responsible for activating the receptors in the mouth. Thus they have developed instrumental methods for measuring the in-mouth behaviour of food materials that give rise to the different sensations in the brain.

There has been significant effort directed towards understanding the links between the bulk material properties of foods before they enter the mouth and their sensory properties (Bourne, 2002; Moskowitz, 1987). Recent work has been conducted to study the changes in the properties of the food materials during oral processing, whilst the product is 'in use' so as to understand the potential impact of these changes on the sensory perception of the product (de Wijk *et al.*, 2003; Engelen *et al.*, 2003a; Engelen *et al.* 2003b; Lucas *et al.*, 2002; Peleg, 2006; van Vliet, 2002). Many such studies involve instrumental measurements of samples outside the complex environment of the mouth. For instance, mixing food samples with saliva *ex vivo* allows the effects of dilution and enzymatic activity to be studied under controlled conditions. These studies give good indications about the behaviour of foods in the mouth. However, they cannot fully capture the complex nature of the natural mastication process with the complex salivary flow patterns and the adaptive and responsive nature of both the chewing action and saliva production. Measurements made *in vivo*, as the food is being consumed (or directly after consumption), can reinforce the knowledge obtained from the *ex vivo* and *in vitro* measurements. Whilst *in vivo* measurements do fully capture all of the processes that are involved in the consumption of food, they suffer from other limitations. Human variability is an issue with any *in vivo* assessment and large subject numbers are often required to counter this variation. Using a real human mouth as the processing component of the experiment also does not allow the same freedom to explore individual factors as *in vitro* measurements. Controlling the shear rate with a human subject is not as easy as in a rheometer, for example, and the range of formulations that can be tested *in vivo* is restricted due to ethical issues and the palatability of the samples.

To select the appropriate measurement method requires an understanding of the way that food is processed in the mouth (Duran and Costell, 1999). Various techniques have been developed and are discussed later in this chapter. There is a need to understand both the anatomy and physiology of the mouth to appreciate the volume of the mouth, saliva flow rate, mastication, amount of food consumed and swallowing, on the transport of food through the mouth. These aspects are covered by other chapters in the book and the reader is also referred to recent reviews and papers on the subject (Blissett *et al.*, 2006; Linforth *et al.*, 2005; Lucas *et al.*, 2002; Prinz and de Wijk, 2004; Prinz and Heath, 1999).

There is a growing appreciation that many of the factors involved in oral processing of foods are interlinked. For example, the gel strength of a food will potentially affect the initial texture perception at first bite, as well as the release of tastants and the rate of release of aroma. Other factors like melting time in the mouth may also be linked to gel strength. These interlinked relationships at the structural level are also a feature of perception, and it is now well-established that there are strong neural interactions between the taste and aroma stimuli in the higher regions of the brain (Dalton *et al.*, 2000; Hort and Hollowood 2004; Rolls and Baylis 1994; Small *et al.*, 2004). For these reasons, a multi-variate approach to in-mouth measurement is advisable if we are to fully understand the processes occurring during eating.

9.2 MECHANISMS FOR SENSING AND MEASURING TASTE

Taste sensations are due to the presence of certain chemicals in our food that trigger specific receptors on the tongue. It is generally believed that the role of taste is to assess food prior to swallowing, so as to select nutritious food and reject potentially poisonous food, although the system is not wholly effective. The taste receptors are located in the taste buds on the



Figure 9.1 Visualisation of taste papillae (the raised dots) using blue food dye. For a colour version of this figure, please see Plate 9.1.

surface of the tongue. These structures can easily be visualised by applying blue food dye to the tongue with a small paint brush; the taste buds usually appear as raised white dots on a blue background (Figure 9.1). There are now five recognised tastes; sweet, sour, bitter, salt and umami. Taste is sensed when molecules of the tastant are transported from the food to the receptors (located on the tongue) by the saliva phase that surrounds the food.

9.2.1 Taste thresholds

To create a perceptible signal from the taste receptors, a minimum quantity of tastant is required. This is defined as the 'taste threshold' and there are well defined methods to determine this factor using sensory protocols (Kemp *et al.*, 2009). Since humans vary in their sensitivity to tastants, taste thresholds are usually measured as the level at which 50% of the group can detect the tastant. There are large variations in the published values, presumably due to different genetic and experiential factors. For the common sweet, acid and salt tastes, the thresholds measured are in the range of grams of tastants per 100g of food. Sucrose taste thresholds from several published studies ranged from 0.017 to 0.56g/100g while sodium chloride threshold was from 0.016 to 0.234g/100g (Kelty and Mayer, 1971). High intensity sweeteners have thresholds that can be hundreds or thousands of times lower than sucrose, while some bitter compounds can also be detected at very low levels (Schmiech *et al.*, 2008). Now that some taste receptor structures are known, the idea of a single site for a sweet molecule to bind to has been replaced by the multi-site hypothesis (Cui *et al.*, 2006). Measuring the taste threshold of individual compounds therefore provides some information on their activity, but the presence of other compounds may well modulate their effects. The umami receptor offers a good example of multi-site receptors where the binding of monosodium glutamate and certain nucleotides causes enhanced signal output (Zhang *et al.*, 2008). The consequence of taste thresholds and multi-site binding for oral processing is that it provides an understanding of the types of stimuli that need to be measured and the sensitivity needed for instrumental techniques to monitor the release of tastants *in vivo*.

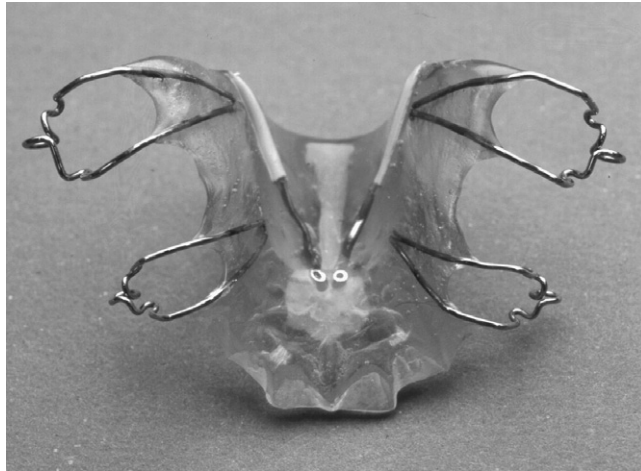


Figure 9.2 Dental plate with embedded electrodes to monitor salt and pH during eating. The four wire loops attach the plate around the teeth; the plate rests on the upper palate and wires from the electrodes (not visible) are led out of the side of the mouth. For a colour version of this figure, please see Plate 9.2.

9.2.2 Food structure, oral breakdown and tastant release

Food structure affects the way food breaks down during oral processing and will therefore affect the way tastants are released from the food and, ultimately, the perception of taste. This is important as the interactions between the taste sensation and the other attributes (aroma, viscosity etc.) build the overall impression of flavour in the brain and a change in tastant release can affect the overall perceived flavour (see later section on multi-sensory interactions).

Measurement of taste in the mouth generally involves sampling the saliva phase on the tongue and analysing the samples for taste chemicals such as salt, sugar, acids and so on. For salt, ion electrodes give good selectivity and have been installed in dental plates (Figure 9.2) to monitor the salt content of saliva during eating (Jack *et al.*, 1995; Davidson *et al.*, 1998). In practice, the technique has some drawbacks. If mounted in the roof of the mouth, the electrode is not in close contact with the saliva phase that coats the tongue and the measured levels may not reflect the signal that reaches the taste buds. Early electrodes were also prone to breakage and there was a risk that fragments could be swallowed by panel-lists. The current electrodes are flexible and robust but they still need wires to transmit their signal to the outside world and some panellists find it difficult to chew with wires coming out of their mouths. Incorporation of wireless communication into these devices should improve this aspect in the future.

Alternative methods for in-mouth sampling have been developed to avoid the use of wires and involve sampling saliva from the tongue at various times and at specified locations. Tastant composition of the samples can be analysed using conventional Liquid Chromatography-Mass Spectrometry (LC-MS). Swabbing the tongue using pre-weighed cotton buds (designed for cosmetic use) has proved successful for some foods (Davidson *et al.*, 2000). Subjects chew the food, then swabbed samples are taken from the tongue at specified times and, through replication, a full picture of release can be constructed. Extraction and analysis of the tastants produces many samples and the process has been simplified to allow high throughput analysis using a direct mass spectroscopic technique (Davidson *et al.*, 2000; Taylor *et al.*, 2000). A typical plot of tastant release against time is

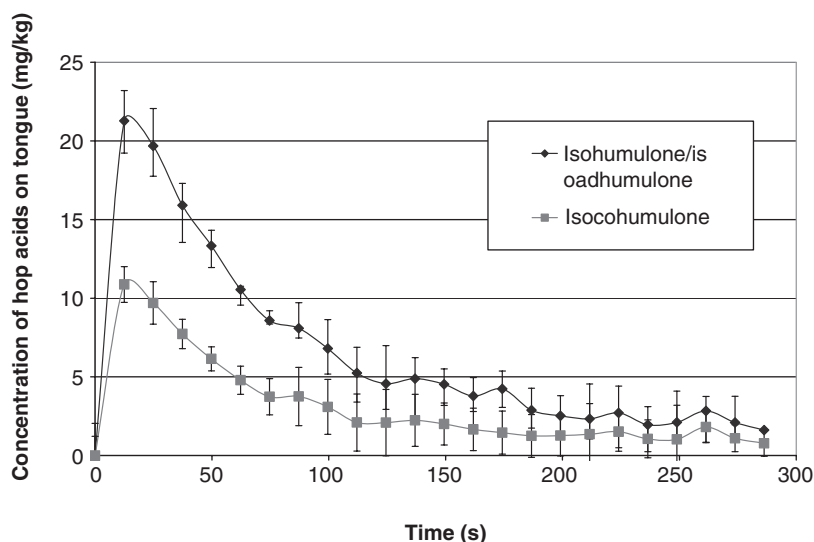


Figure 9.3 Tasted release profile of hop acids from beers during and after consumption of a single aliquot of beer (20 ml). Data points are the mean values obtained from one panellist and error bars show the standard deviation across four runs (unpublished data from Taylor, reproduced with permission).

shown for beer samples in Figure 9.3 where the persistence of hop acids can be seen. This technique has been utilised to study how the structure and composition of foods affect the tastant profile during consumption and has provided complementary information to sensory analyses of the same samples. For instance, the poor sensory performance of a reformulated beverage could be attributed to the persistence of bitter compounds on the tongue and, with this knowledge, various strategies were developed to solve the problem (unpublished data). The technique is limited to liquid foods or foods that form a distinct semi-solid bolus, like chewing gum, with a clearly defined liquid phase. Those foods which are viscous (e.g. chocolate) and remain on the tongue for some time, make it difficult to know whether the sample taken from the mouth reflects the saliva composition reaching the taste bud or the composition of the food itself.

True on-line sampling and analysis of tastants has not yet been achieved *in vivo* due to the complexities described above. *In vitro* techniques using either the so-called electronic tongue (Winqvist *et al.* 2000; Deisingh *et al.*, 2004) or model mouths (Mielle *et al.*, 2010; Rabe *et al.*, 2002; Roozen and Legger-Huysman, 1997; Salles *et al.*, 2007) provide alternatives, but always need to be related to the situation that occurs *in vivo* (Deibler *et al.*, 2001). Given the significant advances in the molecular biology of taste receptors and the availability of receptors expressed in host cells (Meyerhof and Richter, 2006), the possibility of building *in vitro* systems using functional taste receptors is upon us and we can expect significant advances in this area in the near future.

9.3 MECHANISMS FOR SENSING AND MEASURING AROMA

Aroma is sensed by humans using the ortho- and retronasal routes, which correspond respectively to the smell of food before eating and the aroma sensed during eating. The

orthonasal route involves air entering the nostrils and being transported to the olfactory receptors located high in the nasal passages. The retronasal route involves aroma release in the mouth and subsequent transport of aromas into the throat and then to the olfactory receptors. Aroma transport via the retronasal route is therefore affected by the oral breakdown of food in the mouth, which in turn is affected by the physiological and anatomical differences in humans, such as different air flow rates and different chewing and swallowing behaviour.

Depending on the product, the two routes can have different levels of significance. Wine 'bouquet' (orthonasal) is an important part of wine flavour perception whereas, in chocolate flavour, the retronasal route is more important. The signals from both routes contribute to overall flavour quality and there is evidence that when aroma compounds are administered by the different routes, they are perceived differently (Buettner *et al.*, 2002; Heilmann and Hummel, 2004; Hummel *et al.*, 2006; Small *et al.*, 2005).

Unlike the sense of taste, where there are five basic tastes, aroma is more complex and the human olfactory epithelium contains about 350 different aroma receptors. Complex aromas are sensed as qualitative and quantitative signal patterns from the receptors (Breer, 2003). Each receptor shows a broad specificity and will bind an aroma to a degree determined by its gas phase concentration. This differential binding provides a broad dynamic range for quantitative measurement of aroma concentration as well as providing unique qualitative patterns for aroma recognition (Araneda *et al.*, 2000). The receptors are much more sensitive than the taste receptors with odour thresholds in the parts per billion range (gas phase concentrations of nanolitres of aroma per litre of air). Some sulphur-containing compounds have extremely low aroma thresholds (picolitres of aroma per litre of air) and values can be found in compendia of published values (Devos *et al.*, 1990; Rychlik *et al.*, 1998; van Gemert and Nettenbreijer, 1977).

Aroma release can be followed as the chemical signal before it reaches the receptor or as the neural signal that reaches the brain after the receptor. In humans, functional magnetic resonance imaging (fMRI) of brain regions is the method of choice and studies have shown the brain response to various mouth stimuli such as taste (Rolls 1997), aroma (Cerf-Ducastel and Murphy, 2001) and texture (Rolls *et al.*, 1999; Rolls, Verhagen, and Kadohisa, 2003). Because muscle movements interfere with the MRI signal, most studies have not involved eating or swallowing. A recent development allows subjects to receive taste and aroma stimuli in a more realistic way while still allowing fMRI scanning (Marciani *et al.*, 2006). The same paper emphasises the importance of swallowing in transporting the aroma signal from the mouth to the nose when subjects are supine. There is a tendency to close off the throat from the mouth to prevent liquids entering the lungs when subjects are lying down, thus preventing transport of aromas to the receptors via the retronasal route. The development of alternative brain scanning devices where the subject sits upright (e.g. magnetoencephalography) will overcome the supine/upright problem while offering advantages in speed of neural monitoring. This area is developing and can offer excellent insights into the way in which signals from the mouth and nose are processed in an interactive way (Small *et al.*, 2004) to produce the overall perceptual signal.

Monitoring the chemical signal that reaches the olfactory receptors as food is eaten has been studied extensively over the last ten years with the advent of techniques to measure aromas in the gas phase, directly and in real time. Rather than trap volatile aromas and analyse them by time-consuming gas chromatography-mass spectroscopy (Ingham, Linforth, and Taylor 1995), a direct MS technique based on atmospheric pressure chemical ionisation (APCI) was developed at the University of Nottingham (Linforth *et al.*, 1996; Taylor and



Figure 9.4 Using the MS-Nose instrument to sample aroma release during food consumption. Reproduced with permission.

Linforth, 2003; Taylor *et al.*, 2000). Since then, other direct MS techniques have become available for aroma analysis such as proton transfer reaction (PTR)-MS (Taucher *et al.*, 1996; Mayr *et al.*, 2003) and selected ion flow tube (SIFT)-MS (Milligan *et al.*, 2007; Spanel and Smith, 1999) and the scientific literature contains reports on aroma release from a wide variety of food systems. To monitor aroma release via the retronasal route, the technique samples expired air from the nostrils of people eating food (see Figure 9.4) and delivers a 'breath by breath' profile of aroma release during the eating process, at least for those compounds that can be detected by the MS system. The concept is that the aroma profile in expired air is very similar to the profile experienced by the olfactory receptors in the nose and this should correlate better with sensory perception (Taylor and Hort, 2004). Aroma release by the orthonasal route can also be measured with these on-line MS techniques (van Ruth and Roozen, 2002) but this area is not covered in detail here.

Aroma release from food structures, especially those based on fat, have received considerable attention due to the need to produce 'healthier' foods with a lower fat content but with acceptable flavour. Emulsion systems have been investigated to determine the role played by fat as it affects food viscosity (Bayarri *et al.*, 2007) and oral breakdown (due to phase inversion or fat melting point) as well as acting as a solvent for the more hydrophobic aroma compounds (de Roos, 2000). The effect of fat on aroma release has been measured in simple, *in vitro* model emulsion systems (Carey *et al.*, 2003), *in vivo* (Doyen *et al.*, 2001) and as a function of oral physiology (Geary *et al.*, 2002). Since emulsions carry both fat and flavour, attempts to modify emulsions to reduce the fat content while delivering flavour and other food ingredients (e.g. bioactives) have been studied (Appelqvist *et al.*, 2007). One outcome of these measurements is the realisation that oral processing has significant effects on aroma release that are not easily explained by *in vitro* experiments. An example is that the apparent aroma partition *in vivo* is compound-dependent and not easy to relate to *in vitro* values (Doyen *et al.*, 2001).

Aroma release measurement during consumption of real foods with low and regular fat levels demonstrates the inter-related effects of composition and structure on aroma release. Aroma release from milks with different fat contents was measured *in vivo* and correlated to overall sensory performance (Miettinen *et al.*, 2004). Low and regular fat yoghurts showed that aroma release was similar for 3.5 and 10% fat samples but, between 3.5% and

0.1% the reservoir effect of fat was lost and aroma release was higher and of shorter duration (Brauss *et al.*, 1999). Biscuits showed a similar pattern but, here, hydration of the dry sample was an important factor in aroma release of certain aroma components (Brauss *et al.*, 2000). There is also data which shows that the microstructure of biscuits, created through a combination of composition and processing variables, also has a significant effect on flavour perception, part of which is due to a change in aroma release (Burseg *et al.*, 2005; Burseg *et al.*, 2009). Thus the composition and/or microstructure of foods can change aroma release and, in some cases, this leads to changes in perception (see later section on multi-sensory interactions).

The effect of oral processing on sensory perception of foods was reported by Burdach and Doty (Burdach and Doty, 1987) but the studies could only measure mastication 'input' and sensory 'output' with no information on aroma or tastant release. *In vivo* aroma release measurements during eating are now considered routine and part of the toolbox that helps us understand how composition and structure determine the sensory properties of foods (Buettner *et al.*, 2008). They have been applied to study the physiological processes relating oral processing to aroma release and to mathematical modelling of *in vivo* aroma release. In the former case, measurements of nasal air flow, swallowing and chewing were used to assess how aromas were transferred from mouth to nose as well as estimating the volumes of air that were transferred (Hodgson *et al.*, 2003). Depending on the type of oral processing, volumes transferred ranged from 26 mL to 75 mL. Attempts to correlate models of aroma release with actual measurements have had varying degrees of success. The complexity of the chemical, physical and physiological mechanisms that occur in mouth during eating are difficult to achieve using mathematical models based on classical mass transfer processes (Linthorpe 2010). Some success has been achieved in predicting release from food microstructures where a mathematical model was confirmed by measurements of aroma release *in vivo* (Lian *et al.*, 2004). Aroma persistence has also been successfully modelled (Normand *et al.*, 2004; Wright *et al.*, 2003). The effects of viscosity on aroma persistence (Buettner and Mestres, 2005) are of potential commercial interest as products like cough sweets rely on prolonged aroma persistence for their effect.

9.4 MECHANISMS FOR SENSING AND MEASURING TEXTURE

Texture perception is due to the response of mechanoreceptors to the mechanical deformation of the oral mucosa in which they lie. Mechanoreceptors are present throughout the oral surfaces, the lips, tongue and gums. There are three types of mechanoreceptor in the mouth that each respond differently to forces and pressures experienced during mastication: fast-adapting type I, fast-adapting type II and slow-adapting type II receptors (Trulsson and Essick, 1997). Similar to the receptors in skin, type I receptors respond to pressure applied over a small area and are responsible for tactile acuity. The fast-adapting type II receptors respond to changes in pressure whilst the slow-adapting receptors give a continued response to a constant applied pressure over a larger area. All are likely to be involved in the detection and evaluation of food texture. The feedback that is received from the mechanoreceptors enables the consumer to adjust their bite force and chewing action to allow for the most efficient bolus formation (Nicosia and Robbins, 2001). As well as its functional role, texture perception is also key to consumer preference, with foods commonly being described in textural terms such as astringent, gritty, slimy, smooth or creamy.

As described above, the breakdown of soft food gels has an impact upon the perception of aroma and taste. The initial breakdown properties will also impact on the textural perception of the product. Measurement of bite force is an active area within dental research (see for example (Gambareli *et al.*, 2007)). Many of these dental studies involve sensors embedded into partial dentures (Akca *et al.*, 2006; Morneburg and Proschel, 2002), however, measurements can be made by simply attaching pressure sensors to the teeth with denture fixative (unpublished work) although again this necessitates wire connections to the readout equipment. Other measurements involve using microneurographic techniques to read the output from individual mechanoreceptors (Johnsen and Trulsson, 2005) although this is somewhat more invasive. Data from such experiments can then be combined with *in vitro* fracture studies and sensory data to correlate with perception of softness, crispness and so on.

Textural descriptors such as smooth or slimy are often used to describe soft materials. Such parameters might be expected to be correlated to the material's rheological properties. The complicated flow patterns in the mouth and the effect of dynamic changes during consumption (e.g. dilution by saliva or breakdown by amylase activity) make a direct link between instrumental measures of bulk rheology and the in-mouth behaviour difficult. There are currently no direct measurements of the flow profile inside the mouth during mastication. Since most liquid foods are non-Newtonian, in order to make links between instrumental measures of rheology and sensory properties, assumptions must be made about the types of deformation and shear rates in the mouth. By comparing the sensory perception and steady shear rheological behaviour of Newtonian and non-Newtonian fluids, Shama and Sherman identified the shear rates that are likely to be important during texture discrimination (Shama and Sherman, 1973). This is a useful approach but neglects, for example, the elongational flows that are likely to be present during oral processing (van Vliet, 2002). A simple theoretical model based on tongue to palate movements was developed which included some extensional flow considerations (Elejalde and Kokini, 1992). In viscous liquid systems, correlations were obtained between measurements considering elongational flow components and sensory perception of texture (Kokini and Cussler, 1983) and overall flavour (Cook *et al.*, 2003).

An alternative analytical technique which may mimic oral processing is vane rheometry where the geometry between the vane and the sample container creates a more complex rheological situation. The cross-shaped vane tends to move the bulk of the liquid as one component while creating shear flow close to the walls. Proponents of vane rheometry claim that this provides a more complete analysis than conventional bulk rheometry, although there is a degree of empiricism involved. The technique does correlate well with sensory data in real food products like yoghurt (Martin *et al.* 2005) and Figure 9.5 shows correlations between the sensory and vane properties of a range of commercial yoghurts of different fat and hydrocolloid compositions.

When soft food materials are consumed, much of the oral processing involves the compression of the tongue against the other surfaces of the mouth resulting in a thin film of product between the oral surfaces. In this region, rather than bulk rheological properties being dominant factors, the material characteristics are those of thin films and measurement using narrow gap rheological or tribological methods may be more appropriate. For example, recent work has demonstrated that, whilst bulk rheology is matched for full-fat and low-fat mayonnaises, there are significant differences in their lubrication properties (Figure 9.6) (Bongaerts *et al.*, 2007). It should be noted, however, that the bulk rheology data were acquired at low shear rates whereas the lubrication data are valid for higher

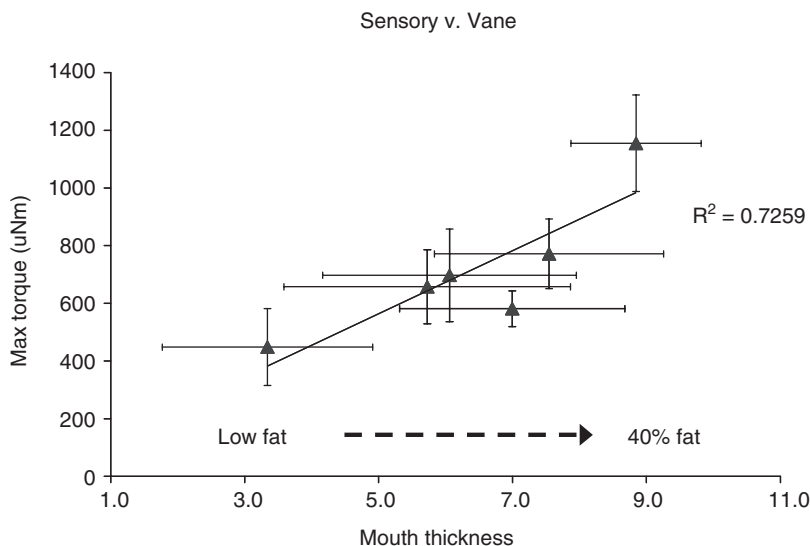


Figure 9.5 Mouth thickness measured by a trained sensory panel (seven people, four replicates each) correlated with maximum torque from vane rheometry of a range of six commercial yoghurts. Unpublished data but based on the work of Martin *et al.*, 2005, reproduced with permission.

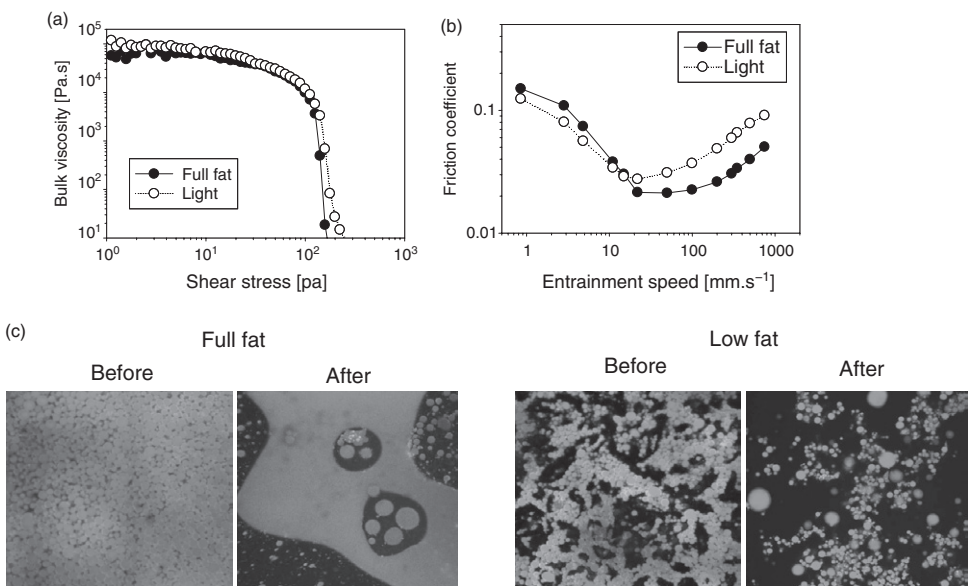


Figure 9.6 Bulk rheological (a) and tribological (b) measurement of full and low fat (light) mayonnaise and (c) confocal microscopy of the structures before and after processing in a rubbing contact, green indicates fat, red protein. From unpublished data from Bongaerts, Houston and Stokes reproduced with permission. For a colour version of this figure, please see Plate 9.3.

deformation rates and correlation (or lack of correlation) with sensory data provides great insight into in-mouth deformation regimes. The breakdown of the structures in a rubbing contact is also very different between the two samples (Figure 9.6). This may indicate that the different sensory performance of these products may be partly explained by their tribological behaviour. A few research groups are now investigating the tribological nature of foods and how this relates to sensory perception (Bongaerts *et al.*, 2007; de Hoog *et al.*, 2006; de Vicente *et al.*, 2006; de Wijk and Prinz, 2005, 2006; Dresselhuis *et al.*, 2008; Dresselhuis *et al.*, 2007; Olsson *et al.*, 1991; Ranc *et al.*, 2006). Many studies are conducted using soft rubber materials to mimic the oral substrates. Whilst these surfaces can be controlled to give a variety of surface chemistries and roughness, they do not mimic completely the 3-D topographical structure of the tongue with its papillae. Prinz has used excised pig tongue and pig oesophagus as tribological surfaces (de Hoog *et al.*, 2006). This moves closer to an approximation of the true situation in the mouth albeit with less control. Simple *in vivo* sliding friction measurements from the oral surfaces have been made (Olsson *et al.*, 1991), however, there is currently no true *in vivo* tribological technique available.

9.5 MULTI-SENSORY INTERACTIONS

Measuring the individual stimuli (taste, aroma and texture) in the mouth provides some information on the role of the stimuli in the perception of soft food materials. However it is well-established that there is significant interaction between the neural signals from the individual stimuli when they are processed either locally in the mouth or in the brain. Our perception of food is technically defined as 'multi-modal' (a modality is a stimulus) with 'cross-modal' interactions (Delwiche, 2004; Taylor and Hort, 2004).

There are several published examples of the phenomenon. Oral temperature can affect the sensory perception of a food, either by changing the physical properties of the food materials (such as viscosity or the volatility of aroma compounds) and/or by impacting upon the sensitivity of the receptors to stimuli. Heat activation of sweetness perception has been reported (Talavera, 2005) and cooling can also affect the perception of other stimuli, either caused by physical means (Green and Frankmann, 1987) or by chemical cooling compounds (Green, 2004).

There are also numerous reports of the effect of viscosity on flavour perception in soft food materials. The reports originated from sensory analyses which showed that, for most food grade thickeners, flavour intensity decreased as viscosity increased (Pangborn and Szczesniak, 1974). When rheological analyses were applied to examine the potential causes and mechanisms behind the observation, it was discovered that perception decreased when the C^* value was exceeded (Baines and Morris, 1988, 1989). C^* is the concentration of hydrocolloid at which the polymer chains start to entangle and the point at which the viscosity increases dramatically as hydrocolloid concentration increases. From these measurements, various hypotheses were proposed and these have been tested over the years.

One hypothesis was that viscosity affects the release of aroma or taste signals in mouth. Measuring aroma release *in vivo* (Cook *et al.*, 2002; Hollowood *et al.*, 2002) has shown that the maximum intensity of aroma release is not affected by viscosity (at least in the ranges of interest). This led to consideration of the situation in the mouth where aroma release occurs from thin layers of saliva and where partition is the major physiochemical driver for release (partition is not affected by viscosity and this may explain the observed results of aroma release from viscous solutions). Release of tastants, however, occurs via

a different mechanism where viscosity may interfere with tastant transport from the food to the taste receptors. The effect of various food grade thickeners on tastant release has been studied (Ferry *et al.* 2004; Ferry *et al.*, 2006a; Ferry *et al.*, 2006b) and release seems to depend on the ability of the viscous solution to mix with the saliva phase (Mitchell *et al.*, 2008).

A second hypothesis suggested that texture itself may be a stimulus which can modify the perception of flavour (Weel *et al.*, 2002) as, in the system used, no added tastant was present. There has been a suggestion that, although the maximum intensity of release is the same in these systems, the rate of release may be different and this may account for the observed perceptual differences (Buettner and Montserrat, 2005). To try and address these issues, further experiments with emulsion systems were carried out where all emulsions were adjusted to give the same viscosity, aroma release and sweetness, irrespective of fat content (Hollowood *et al.*, 2008). The emulsions were then tested sensorially and some differences were still found despite the careful control of the physical and chemical stimuli from the emulsions. An EU project on texture–flavour interactions used custard as a model system to explore the sensory properties as a function of custard composition and physical properties (Gonzalez-Tomas *et al.*, 2008; Kersiene *et al.*, 2008; Tournier *et al.*, 2009). The nature of the hydrocolloid thickener used was a major factor in most studies. Although the exact nature of these interactions is still not fully understood, the reports in the literature demonstrate the power of in-mouth measurements to understand the interplay between food structure, oral processing and flavour sensing in this type of food material.

Another type of interaction occurs to control mastication of foods, dependent on their texture. This is clear with hard foods like hard-boiled candies, where an initial impression of hardness is obtained by compressing the food between the teeth before people commit to a full-power bite. A similar principle also applies to soft foods where, after initial assessment of texture, a mastication strategy is devised to process the food effectively in the oral cavity. Prinz and de Wijk (2004) showed this in an elegant experiment using different chewing gum samples, which were dyed so that the orientation of the gum strips could be observed during mastication. Subjects chewed the gum strips with the long edge parallel to their teeth whatever the initial orientation and then folded the chewed gum using their tongue.

The effect of food structure and mastication behaviour on aroma release and flavour perception in simple gel systems has been studied in a series of gelatine-sucrose gels with different compositions, and therefore different textures, but with the same aroma content. The samples were eaten using either a fixed mastication protocol or 'freestyle'. Figure 9.7 shows that aroma release *in vivo*, using on-line measurement of aroma release during gel consumption, was dependent on gelatine concentration due to the greater effort required to break down the gel structure. It also shows that the eating protocol can affect release, and the measurement of mastication, airflow and swallowing (Blissett *et al.*, 2006) can show differences in eating behaviours between people. In addition, these experiments showed that whilst the rate of release was different, the maximum intensity of release was not affected by gel strength (Baek *et al.*, 1999). The simple hypothesis which anticipates that sensory differences are related to changes in amounts released does not always hold and a new hypothesis has been proposed that the rate of aroma release is affected by food structure and that perception is most strongly related to rate of aroma release (Baek *et al.*, 1999).

To investigate the effects of aroma release and texture, subjects received aroma stimuli from an olfactometer through a tube which terminated in the nose in different positions (Bult *et al.*, 2007; Buettner *et al.*, 2008) so as to mimic orthonasal aroma delivery (the

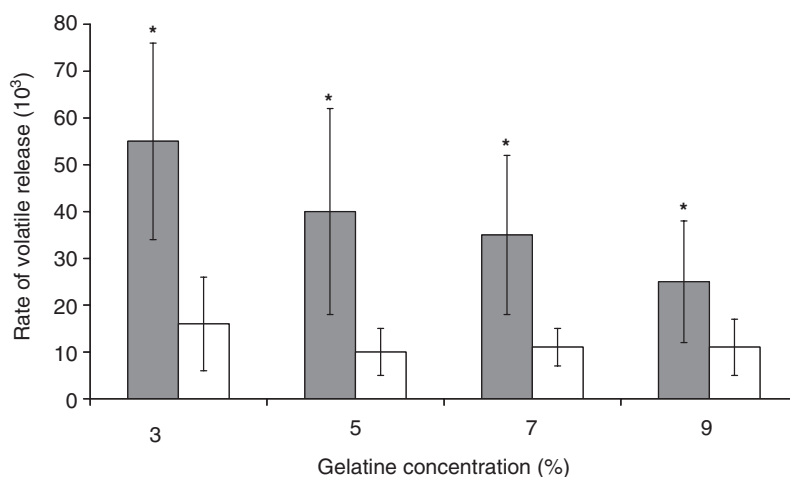


Figure 9.7 Release of ethyl butyrate from gelatine-sucrose gels during free-style (dark bars) or fixed pattern (open bars) eating. Release was measured in the exhaled air from six panellists (three replicates each). Error bars are $\pm$ standard deviation and the star denotes a difference between the two modes of eating at the $p < 0.05$ level. From unpublished data from Blissett and Hort reproduced with permission.

equivalent of sniffing an aroma prior to food consumption) or retronasally (mimicking aroma delivery during eating). At the same time, thickened solutions of different viscosities were introduced into the mouth to deliver a textural stimulus. This experimental approach separated any physicochemical interactions between aromas and viscous liquids. Sensory analysis showed that increasing the viscosity of in-mouth solutions decreased the overall perception of the aromas in the nose, confirming earlier results obtained using mouth delivery of all components (Cook *et al.*, 2003; Weel *et al.*, 2002).

Flavour interactions at the higher cognitive level can now be studied using brain imaging. Understanding how the signals received by the receptors are processed in the brain to elicit the overall sensory impression is a growing area of study (Hort *et al.*, 2008; Marciani *et al.*, 2006; Verhagen, 2007). However, this area is outside the realms of this chapter which focuses on measuring the physical and chemical processes that are occurring in the mouth.

9.6 MEASURING FOOD BREAKDOWN AND DEPOSITION *IN VIVO*

Due to the oral processing that a food material undergoes in the mouth, the material that is being sensed is continually changing and is often very different to the material that first entered the mouth. The way that food products break down to give a structure that interacts with the 3-D structures of the oral cavity during eating is ultimately what determines the physiological stimuli they induce and the resulting sensory perception. Measuring the breakdown process *in vivo* is not trivial because of the mechanical barrier to simple direct imaging formed by the teeth and the movement and mechanical forces that must be endured during the mastication process (Hiemae and Palmer, 2003). Due to the lack of direct access, there have been several attempts to simulate the masticatory process (see for example Mielle *et al.* 2009; Prinz *et al.*, 2007; Salles *et al.*, 2007). Other studies have followed the

breakdown of structures using *ex vivo* techniques such as a chew and spit approach or *ex vivo* mixing. Mowlana and Heath have examined the break-up of solid foods (Mowlana and Heath, 1993) and van Aken's group have examined the structure break-up and formation that occurs upon mastication of emulsions (Silletti *et al.*, 2007; Vingerhoeds *et al.*, 2005). These studies give great insight into the interactions of the food with the oral processes; however, it is the food that remains behind in the mouth, not the food that is swallowed or expectorated, that is interacting most intimately with the oral substrate. New techniques now enable this residual material to be examined *in vivo*.

9.6.1 Imaging food *in vivo*

Video-rate confocal endoscopy has been used to visualise food materials in the mouth allowing real time sub-millimetre resolution images from around the oral cavity (Adams *et al.*, 2007). The technique typically uses laser illumination to collect fluorescent images from fluorescent foods such as some natural oils, vitamins or spices or specially-labelled food materials. The use of a rigid rod endoscope (see Figure 9.8) prevents the collection of images during mastication, but data can be collected from the mouth immediately after food consumption. This in-mouth imaging approach can be used to directly visualise the way in which material is deposited, as well as to measure the amount of food material remaining in the mouth after consumption and how quickly it clears from the mouth; all key aspects to the afterfeel and aftertaste of a product.

Figure 9.9 shows an example of the data that can be obtained from this technique. Figure 9.9a shows the initially deposited amounts of aqueous solutions of different concentrations of carboxy methyl cellulose (CMC), demonstrating that the higher viscosity samples deposit to a greater extent. Figure 9.9b shows the characteristic time it takes a CMC solution containing varying amounts of citric acid to clear from the mouth. The decrease in the characteristic time for clearance is linked strongly to the salivary flow rate, and the visual images collected, give direct observation of the consequences of the physical processes occurring during oral processing.



Figure 9.8 Photograph of a subject using the in-mouth imaging probe to visualise the residue on the tongue after consumption of a food product. Note the rigid rod endoscope that is used to image the tongue surface.

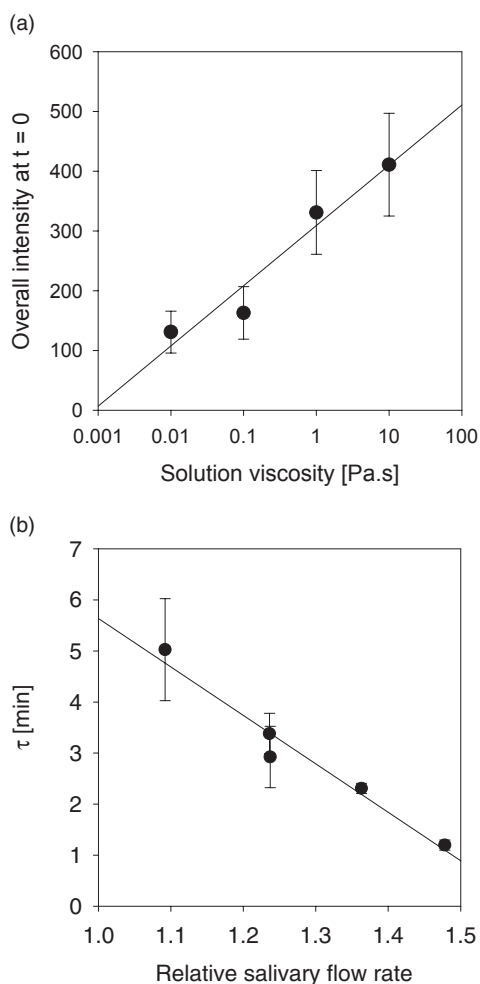


Figure 9.9 Data obtained from in mouth imaging. a) The intensity axis measures the amount of CMC residue on the tongue following consumption and swallowing of CMC samples of different viscosities, b) Characteristic clearance times, τ , for removal of CMC residue from the mouth. CMC solutions of the same viscosity were administered while different salivary flow rates were induced by different citric acid concentrations. Reproduced from Adams *et al.*, pp.986–995, 2007, with permission from Elsevier.

New advances to this technique allow the position of the endoscope on the surface of the tongue to be carefully controlled and tracked using magnetic sensors. This allows the collection of images from specific regions of the mouth and, therefore, the construction of a ‘map’ of the tongue surface indicating which regions show the highest deposition. Figure 9.10 shows an example of this ‘map’ for deposits of food oil from an emulsion system. This spatial information can then be related to the structure of the underlying tongue surface and to sensory descriptions such as prickling at the back of the mouth, as observed for astringent materials. Creating a map as a function of time allows us to probe the path that material follows en route to being swallowed and will allow for correlations with time

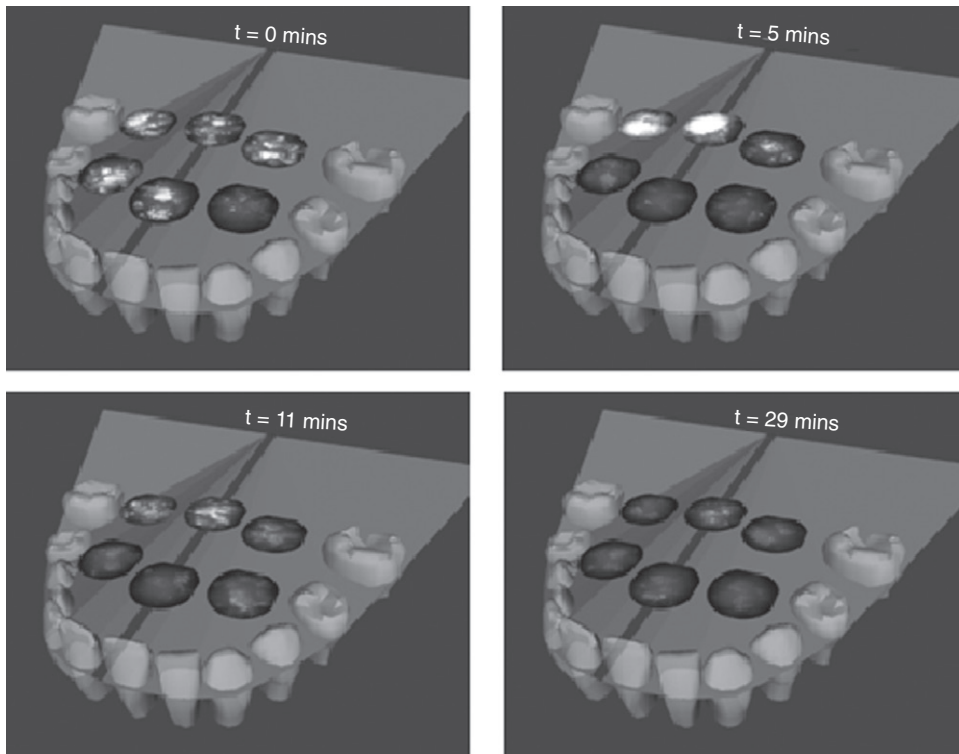


Figure 9.10 Spatial maps of oil residue on the tongue surface at various times (0, 5, 11 and 29 min) after oral processing of an emulsion system. The oil images are shown at three times the actual image size (relative to the size of the tongue, actual image width ~ 1.5 mm).

intensity sensory data. As with all techniques, there are limitations to the food systems that can be studied.

Prinz *et al.* have also developed a technique to measure food residues *in vivo*. They used opto-electronic reflectance sensors placed on the tongue surface to gain a measure of the residue thickness (Prinz *et al.*, 2006) again giving information on residue amounts. Alternative methods for determining the residues of food inside the oral cavity involve scraping or swabbing the tongue surface after consumption of the food and analysing the residue *ex vivo* (de Jongh and Janssen, 2007). Whilst this approach is more invasive than imaging the residue *in situ*, it does allow for selective analysis of different components.

9.6.2 Spectroscopy of food components *in vivo*

The data obtained from the fluorescent imaging technique described above allow the deposition and clearance of the labelled phase to be followed. However, specific chemical information about the identity of the components that make up that phase is not available. Spectroscopic analysis of the oral mucosa would allow for discrimination of the components of a food material that are deposited. Fourier-transform infra-red (FTIR) spectroscopy has been applied to study the oral mucosa *in vivo* (Yoshida *et al.*, 1999; Yoshida and Yoshida, 2004). Yoshida developed an attachment to enable attenuated total reflectance

FTIR data to be collected directly from the inside of the lip. The reported studies are focused on the analysis of the spectra generated from the oral mucosal tissue itself and its potential applications in medicine. However, one can envisage that such a technique could be applied to the oral substrates after consumption of various foods to great effect.

9.6.3 Following mastication *in vivo*

The actions of the mouth during mastication and swallowing have been shown to have an impact upon sensory discrimination of foods (de Wijk *et al.*, 2003). These motions can be followed *in vivo* giving additional information on the mechanisms involved in food breakdown. An ultrasound device has been used to follow the movements made during the oral processing of model foods and it was found that the type of oral processing performed did depend upon the attributes of sweetness and thickness of the samples used (de Wijk *et al.*, 2006).

There are other techniques and advances within the medical community that follow the mastication and swallowing processes. Video-fluoroscopy allows video rate images to be collected of the jawbones and barium meals inside the mouth during mastication. The technique involves the use of x-ray imaging, so is not widely applicable to the study of foods. However, useful knowledge of the mechanisms of mastication can be obtained from such sources to add to our understanding. For example, images can be obtained of the barium meal during its consumption, which allows for evaluation of the bolus formation and the coating remaining on the throat after swallowing (Hiemae and Palmer, 1999; Kelly *et al.*, 2006). Magnetic resonance imaging has also been used to examine the masticatory muscles, although only whilst the jaw is stationary (Goto *et al.*, 2005).

Ex vivo measurements can also be useful to follow the mastication process. For example the efficiency of the mastication process in mixing products can be assessed by chew and spit studies. Prinz's chewing gum with multi-coloured layers clearly showed the effect of mastication on gum-base mixing (Prinz, 2004). The key finding was that gum was rotated by the tongue and placed in a specific orientation between the teeth for the next chew depending on the shape of the gum piece. This is a clear demonstration of the interaction of mouth-sensing and mastication behaviour. The same lab has also developed image analysis tools to examine the mixing of fluid or soft solid foods in the mouth (de Wijk *et al.*, 2006). The degree of mixing is followed by capturing and analysing images of expectorated samples of foods which contain a small quantity of unmixed suspension of activated carbon black after a certain controlled degree of mastication; see Figure 9.11.

9.7 BIOCHEMICAL FLAVOUR CHANGES DURING ORAL PROCESSING

Changes to starch caused by oral amylase activity have been reported by several research groups (Ferry *et al.* 2004; Ferry *et al.*, 2006b; Tietz *et al.*, 2008). As discussed in Section 9.4, food viscosity is known to affect flavour perception but, in the case of starch based systems, although sensory thickness was positively correlated with amylase activity, sensory perception of saltiness did not increase as viscosity decreased. This apparent contradiction to the observations of other hydrocolloids was attributed to poor release of salt from the starch (Mitchell *et al.*, 2008). Microscopic imaging of the starch structures, after amylase treatment, indicated that the residual starch showed poorer mixing behaviour with saliva,

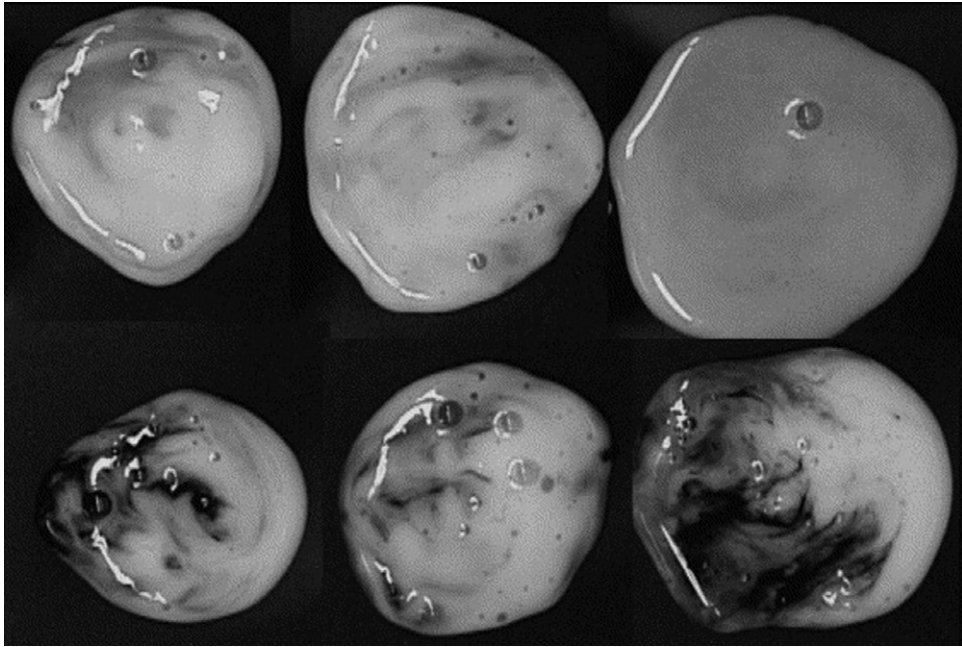


Figure 9.11 Examples of expectorated samples showing mixing during oral processing of low fat (top row) and high fat (bottom row) custards to which a drop of carbon based dye was added (de Wijk *et al.*, 2006). Left, oral residence time of 5 seconds, middle, 10 seconds and right 20 seconds.

thus reducing the amount released *in vivo*. Therefore, oral processing can affect flavour perception by enzymatic means as well as by physical means.

It has been assumed that the aroma and tastants in food are not chemically changed during oral processing. However, the presence of a wide range of enzymes in the nasal mucus (Zhang *et al.*, 2005; Thornton, Manning and Dahl, 1997) capable of degrading aroma compounds (for example cytochrome P450 and dehydrogenases) plus the known metabolic potential of saliva and enzymes contributed by the oral microflora, suggest that some degradation or transformation may take place. Hydrolysis of some glycosidic flavour precursors can occur *in vivo* (Alston *et al.*, 1998; Hemingway *et al.*, 1999) through the action of natural glycosidases.

The effect of oral enzyme activity on a range of flavour compounds was investigated by Buettner (Buettner, 2002a, 2002b). Thiol compounds were particularly affected by a 10-minute treatment with saliva, but heat-treated saliva caused no change, implying an enzymatic mechanism. There were significant differences between panellists suggesting that the enzymatic activity varied. Whether the enzymes results from the natural microflora in the mouth or from saliva itself is not yet established. Reduction of aldehydes to alcohols was also observed with the magnitude of the effect depending on the individual panellist as well as the concentration applied.

A Givaudan patent describes the use of a cytochrome P450 inhibitor to ‘modulate’ the aroma of a product in the nasal cavity. Metabolites can be observed within seconds of the administration of odours to the nose, and inhibiting the cytochrome P450 enzymes causes

not only a change in the chemical composition of the odour mixture but also a change in sensory perception (Schilling *et al.*, 2008). Whether such transformations occur in the oral cavity is not currently clear. Changes to thiols during consumption have been reported (Ito *et al.*, 2009). When a drink containing 4-methoxy-2-methyl-2-mercaptobutane was drunk and swallowed by panellists, a new methylthio ether compound, (1-methoxy-3-methyl-3-(methylthio)butane) was detected in exhaled air, a phenomenon observed with other thiol compounds. The concept that the perceived odour of a food might change during consumption merits further investigation. However, in the latter case, working with sulphur compounds requires great care in the analysis so as to achieve the necessary sensitivity and not create artefacts during extraction and analysis of the analytes. Thiol compounds in meat flavour have also been shown to bind to the thiol groups on meat proteins (Mottram *et al.*, 1996), but whether oral processing affects release or changes in these compounds is not known.

9.8 APPLICATIONS OF KNOWLEDGE TO REAL FOOD PRODUCTS

New and improved techniques for *in vivo* measurements for food applications are being developed continually. The idea of correlating *in vivo* instrumental measurements with sensory properties of foods, the so-called 'human-machine' interaction, has been recently reviewed (Ross, 2009). Each new advance gives additional information and increases our understanding of the mechanisms, processes and interactions that are at play during consumption and sensory evaluation of foods. The information gained from these techniques can be used, together with information from *in vitro* and sensory measurements, to give real benefit to the food industry and the consumer. Some examples of real food applications have been given in the preceding sections and there is much activity into understanding how foods behave in mouth so that low fat, low sugar and low salt foods can be manufactured with acceptable flavour properties. Measuring food attributes in mouth and then applying new formulations has proved successful in flavoured milk using a large consumer panel of 90 people (Shojaei *et al.*, 2006). The launch of a new chewing gum with long-lasting flavour (Cadbury Adams Stride gum) shows the advantages of understanding the flavour release characteristics of aromas and tastants from food matrices during oral processing. The principles were established in earlier work where the link between sweetness delivery in mouth and overall flavour perception was demonstrated (Davidson *et al.*, 1999). More examples will be evident in the next few years as both academic and industry researchers address the challenges of delivering tasty food that is aligned with nutritional guidelines.

9.9 CONCLUDING REMARKS

The processing of food materials in the oral cavity determines how the physical structures and chemical components of a food interact with the flavour sensing mechanisms in the oral cavity. The physiological signals induced by the chemical and physical stimuli in-mouth are further processed to form a multi-sensory construct in the brain (a combination of all the senses) which humans then interpret as a sensory perception. Linking the effects of food composition, oral processing and sensory perception is a long term goal for flavour

scientists. However, measuring the physical and chemical properties of materials in the complex, adaptive and responsive environment of the mouth is no small challenge. Many studies have focused on measurements of the materials before they enter the mouth, or on the sensory assessment of the structures in the mouth. However, there has been much progress in the development and application of *in vivo* physical measurements of food materials. These techniques can give direct access to the real processes occurring during and after mastication and the impact of these processes upon the physical, chemical and sensory properties of the food.

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10 Multi-sensory Integration and the Psychophysics of Flavour Perception

Charles Spence

10.1 INTRODUCTION

Flavour perception is one of the most multi-sensory of our everyday experiences. Taste obviously plays a central role (Lawless, 2001), as does the smell (*aroma*) of a food or drink (Murphy *et al.*, 1977, relying on the transduction of non-volatile and volatile flavour compounds, respectively). Tactile cues regarding the mouthfeel, texture (e.g. sticky, slippery, gritty, etc.), temperature, and burning sensation associated with eating hot foods such as chilli play an important part too (Christensen, 1984; Lawless *et al.*, 1985; Szczesniak, 2002). The sounds we make when eating foods can also influence our perception of the crispiness and crunchiness of foods such as potato chips, crackers and breakfast cereals (see Spence and Shankar, 2010; Spence and Zampini, 2006, for reviews). Visual cues, primarily those related to a food's colour, exert a profound effect on people's perception of the identity and, to a lesser extent, the intensity of a food's flavour (see Spence *et al.*, 2010, for a review).

This article provides a brief overview of the evidence regarding the role of multi-sensory integration in flavour perception in humans. I will review the evidence concerning the multi-sensory integration of olfactory and gustatory cues. I will highlight the evidence showing that changing the colour of a wine can completely change its aroma, or at least the way people describe it (an example of sensory dominance). Examples where multi-sensorially-incongruent combinations of flavour stimuli can lead to foods that taste terrible, and result in a reduced brain response (Skrandies and Reuther, 2008), an example of multi-sensory suppression, will also be discussed. The contribution of multi-sensory integration to flavour perception in humans (and other animals) is an area that has seen a rapid growth of interest from the multi-sensory research community over the last few years (e.g. see Auvray and Spence, 2008; Small, 2004; Small and Prescott, 2005; Verhagen and Engelen, 2006, for reviews). In fact, the techniques of cognitive neuroscience (such as neuroimaging, neurophysiology, computational modelling and psychophysics) are increasingly complementing the traditional techniques of food science. This has led to great progress over the last few years in terms of our understanding of the neural substrates underlying multi-sensory flavour perception.

According to the International Standards Organization (ISO 5492, 1992), flavour can be defined as a 'Complex combination of the olfactory, gustatory and trigeminal sensations

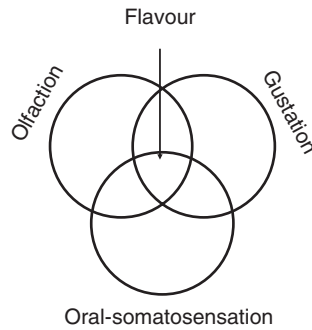


Figure 10.1 According to the traditional view (e.g. ISO 5492, 1992; see also Delwiche, 2004), flavour perception arises from the stimulation of the gustatory, olfactory, and oral-somatosensory (including trigeminal) systems.

perceived during tasting. The flavour may be influenced by tactile, thermal, painful and/or kinaesthetic effects' (see Delwiche, 2004: p. 137). That is, gustatory, olfactory, trigeminal, and oral-somatosensory cues (which represent the activity of distinct interoceptive physiological systems), are the *only* senses that contribute *directly* to the perception of flavour (see Figure 10.1). This is not, of course, to say that visual and auditory cues don't modify a food's flavour, they most certainly do. It is just that they are not, at least according to the ISO definition, integral to it. It should, however, be noted that this narrow definition of the senses integral to the perception of flavour is currently being questioned by some researchers (e.g. see Auvray and Spence, 2008; Stevenson, 2009; see also McBurney, 1986). Part of the reason for this is the emergence of a growing body of empirical research, some of which will be reviewed below, demonstrating just how profoundly the sound of food (and the sounds of food-eating), not to mention its visual attributes (such as its colour), affect our perception of both the sensory-discriminative and hedonic attributes of food and drink.

Furthermore, when talking about olfaction, one critical point to note is that there are actually two relatively distinct sensory systems. The older, *orthonasal*, system associated with the inhalation of external odours and the newer, *retronasal* system (involving the posterior nares), associated with the detection of the olfactory stimuli emanating from the food we eat, as odours are periodically forced out of the nasal cavity when we chew or swallow a food (or drink). A growing body of empirical research now highlights important differences between orthonasal and retronasal smell at both the subjective/perceptual level (e.g. Diaz, 2004; Rozin, 1982), and in terms of the neural substrates involved (e.g. Small *et al.*, 2005; Small *et al.*, 2008; see also Heilman and Hummel, 2004). Both orthonasal and retronasal odour perception are clearly important in terms of multi-sensory flavour perception. It is, however, striking how little thought scientists traditionally gave to whether the odours in their experiments were presented via the orthonasal or retronasal route. In fact, more often than not, olfactants were delivered orthonasally (presumably because it is just much easier). This approach is turning out to be increasingly problematic, however, given mounting empirical evidence that substantially different patterns of multi-sensory integration can sometimes be observed as a function of whether an odour is presented via the orthonasal or retronasal route (e.g. see Bult *et al.*, 2007; Kozla *et al.*, 2005; Pfeiffer *et al.*, 2005).

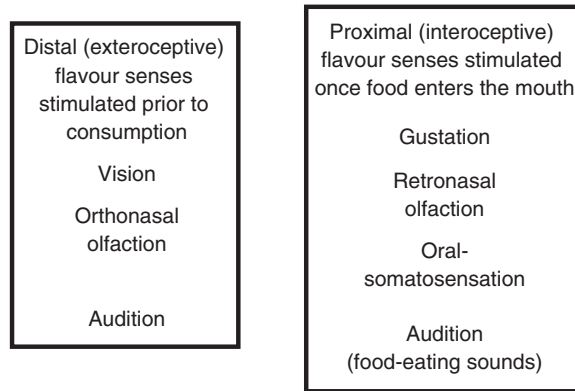


Figure 10.2 One way to conceptualise the role of the various senses that contribute to/influence multi-sensory flavour perception is in terms of a distinction between exteroceptive (or anticipatory) and interoceptive (or consummatory flavour signals; see Small *et al.*, 2008; Stevenson, 2009).

When thinking about the senses and their role in multi-sensory flavour perception, it may help to distinguish between the exteroceptive senses of vision, audition and orthonasal olfaction that are stimulated prior to the consumption of food, and the interoceptive senses of gustation, retronasal olfaction, oral-somatosensation and food-eating sounds that are stimulated while eating and drinking (see Figure 10.2). Different neural mechanisms may be involved in these two cases (see also Small *et al.*, 2008). The multi-sensory integration of interoceptive flavour cues might be less open to cognitive penetration (i.e. it might be more automatic) than the cue combination involved in interpreting exteroceptive cues (though see Auvray and Spence, 2008; van der Klaauw and Frank, 1996). In the sections that follow, I briefly review the evidence concerning the role of each of the human senses in the sensory-discriminative aspects of multi-sensory flavour perception.

10.2 TASTE/GUSTATION

Many researchers believe that humans are sensitive to a number of basic tastes including sweet, sour, salty, bitter, umami (Schiffman, 2002) and metallic (Lawless *et al.*, 2005; Lindemann, 1996). My recent experience eating Sechuan buttons suggests that we may need to add an electric taste as well (though see Keeley, 2002). Traditionally, researchers thought that the receptors for each taste were distributed asymmetrically over the surface of the human tongue (see Guyton and Hall, 1996: pp. 676–78; Mackenna and Callander, 1997: p. 266): sweet taste receptors lying at the front, bitter receptors at the rear, sour receptors to the side of the tongue and so on. It turns out that the various taste receptors are actually far more evenly spaced over the tongue's surface than had previously been thought. The erroneous idea that the receptors were so nicely separated has been traced back to Boring's (1942) incorrect description of early research conducted by Hanig (1901). That said, there is evidence that they may be somewhat more densely packed at the tip of the tongue than elsewhere (Duffy, 2007; Todrank and Bartoshuk, 1991). It is important to note here though that it is no longer clear that each basic taste is necessarily transduced by an individual specialised receptor (e.g. Lindeman, 2001), leading some to query the very notion of basic tastes (see Delwiche, 1996; Erikson, 2008).

Taste (or gustation) is the sense in which one can see the largest individual differences in terms of the number of sensory receptors that people have. Each of the taste buds on the human tongue contains a number of taste cells. The taste buds themselves are located within structures known as fungiform (taste) papillae. Between the upper and lower boundaries, it has been estimated that there may be as much as a 16-fold individual difference in the number of papillae on the anterior tongue of humans (e.g. Miller and Reedy, 1990). People also differ in their sensitivity to certain compounds. Those who are especially sensitive to bitter-tasting compounds such as phenylthiocarbamide (PTC) or the chemically-related 6-*n*-propylthiouracil (PROP) are known as supertasters. It has been estimated that approximately 25% of the population fall into the supertaster category, 50% are 'medium tasters', while the remainder are 'non-tasters'.

While supertasters generally have more taste-buds than non-tasters (Bajec and Pickering, 2008; Bartoshuk *et al.*, 1994), researchers are still uncertain as to the exact relationship between taster status and the density of taste papillae on the human tongue (e.g. Prescott *et al.*, 2004). Supertasters seem to be more sensitive to (or at least rate more intensely the sensation elicited by) other (non-bitter) taste stimuli as well (Bajec and Pickering, 2008). These individual differences in taster status are especially interesting in the context of the present chapter in that they have now been shown to influence certain aspects of multi-sensory flavour perception (e.g. Bajec and Pickering, 2008; Eldeghaidy *et al.*, 2011; Essick *et al.*, 2003; Ishiko *et al.*, 1978; Zampini *et al.*, 2008). Several of these studies will be discussed in the sections that follow.

While it is certainly true that taste plays an important part in the multi-sensory perception of flavour, smell is also critical. In fact, olfactory cues may actually be more important than taste cues, with some researchers estimating that olfactory cues contribute as much as 80% (Martin, 2004; Murphy *et al.*, 1977) to what people normally report as flavour. Indeed, people often confuse the relative contributions of smell and taste to flavour perception (e.g. Davidson *et al.*, 1999; Rozin, 1982; Stevenson *et al.*, 1999). Such confusions have even led some researchers to argue that we may all be synesthetic for flavour (see Auvray and Spence, 2008; Stevenson and Boakes, 2004; Stevenson and Tomiczek, 2007; Verhagen and Engelen, 2006).

10.3 OLFACTORY–GUSTATORY INTERACTIONS IN MULTI-SENSORY FLAVOUR PERCEPTION

Some of the most convincing evidence regarding the multi-sensory integration of orthonasal olfactory and gustatory cues in flavour perception was reported by Dalton and colleagues (2000). The participants in their study were given two pairs of bottles to sniff, each containing a liquid. One bottle contained benzaldehyde which has an almond-cherry like odour, the other three bottles contained diluted solutions with other olfactants. In each trial, the participants had to try and determine in which pair of bottles the bottle with benzaldehyde had been presented. The concentration of the olfactant was varied on a trial-by-trial basis in order to determine each participant's nasal detection *threshold*. In one experiment, the participants had to perform this olfactory discrimination task while holding a 10 ml sub-threshold concentration solution of saccharin in their mouths at the same time. The saccharin solution had no detectable taste or, importantly, odour. Surprisingly, under such conditions, the benzaldehyde odour was perceived as more intense, and hence the partici-

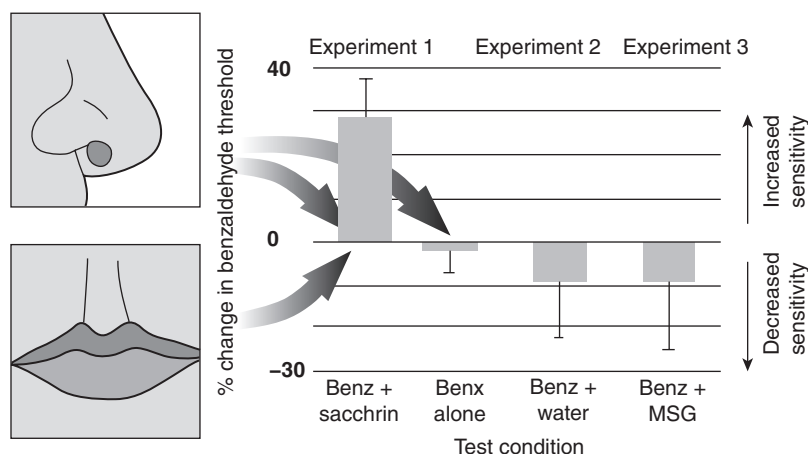


Figure 10.3 This figure highlights the results of a series of experiments conducted by Dalton and colleagues, showing the integration of orthonasal olfactory and gustatory cues (Dalton *et al.*, 2000). When a subthreshold saccharin solution was placed on the participant's tongue, a significant increase in olfactory sensitivity was observed, despite the fact that the tastant had no odour, thus demonstrating the multi-sensory interaction of olfaction and taste. By contrast, holding a small amount of water in the mouth had no effect on olfactory thresholds, nor did holding a solution that happened to contain MSG. These latter results highlight the stimulus dependency (both olfactory and gustatory) of multi-sensory integration in human flavour perception, a result that has now been demonstrated in many other studies.

pants' sensitivity to the odorant went up (while their threshold went down; see Figure 10.3), when assessed relative to a baseline condition in which no tastant was present. The results of a follow-up experiment showed that when the participants kept a little unadulterated water on their tongues instead, it did not result in any change in their olfactory detection thresholds. Similarly, holding a sub-threshold solution of monosodium glutamate (MSG) on the tongue had no observable effect on orthonasal olfactory detection thresholds either. Taken together, these results therefore demonstrate that orthonasal olfactory and sub-threshold gustatory stimuli are subject to multi-sensory integration. However, this multi-sensory effect appears to be specific to the particular combination of olfactants and tastants used.

Dalton *et al.*'s (2000) study provides convincing evidence that sub-threshold gustatory cues can enhance people's orthonasal odour perception. Similar results have now been reported in several subsequent studies (e.g. Delwiche and Heffelfinger, 2005; Pfeiffer *et al.*, 2005). For instance, Pfeiffer *et al.* reported a 50% lowering in the olfactory threshold (that is, they observed complete additivity) in 75% of the 16 participants they tested, provided that the sub-threshold tastant and orthonasal olfactory stimuli (sucrose and benzaldehyde, just as in Dalton *et al.*'s, original research) were presented simultaneously. Pfeiffer *et al.* used a computer-controlled olfactometer and gustometer in order to control the delivery of the odorant and tastant. Similar effects were observed when the odour was delivered retronasally providing, once again, that it was delivered synchronously with the tastant. In their study, Delwiche and Heffelfinger demonstrated similar multi-sensory effects with actual solutions being tasted by participants.

Researchers have subsequently demonstrated that this multi-sensory integration effect depends both on the particular combination of stimuli used, and on the part of the world

in which the participants tested in the study happen to have been brought up: for instance, Japanese participants show these multi-sensory integration effects for the combination of MSG and benzaldehyde (see Breslin *et al.*, 2001; Spence, 2008), but not for the combination of saccharine and benzaldehyde. Note that this is the *opposite* pattern of results to those shown by the North American participants tested in Dalton *et al.*'s (2000) original study! Why should this be? Well, while the typical Western consumer is frequently exposed to the combination of almond-cherry odour and sweet taste in desserts such as Bakewell tart, the combination of an almond smell and a salty taste is far less common. By contrast, in Japan, the combination of an almond odour and a salty taste is common in foods such as pickled condiments, whereas sweet almond desserts are rarely consumed. Labbe *et al.* (2007) have now demonstrated that subliminally presented olfactory stimuli can also enhance sweetness perception. The fact that such effects occur for sub-threshold levels of stimulus presentation rules out a cognitive/expectancy-based account and is instead more consistent with an explanation in terms of multi-sensory integration (cf. Labbe *et al.*, 2007).

These results with sub-threshold gustatory stimuli, highlighting the importance of stimulus congruency, map on to earlier results demonstrating similar multi-sensory interactions between congruent *supra-threshold* combinations of odour and taste stimuli as well. So, for example, Frank and Byram (1988) reported that the presence of a strawberry odour can enhance the sweetness of sucrose delivered in whipped cream stimuli (that participants had to swallow in order to enhance retronasal olfaction) while the odour of peanut butter does not. That is, stimulus congruency (defined by Schifferstein and Verlegh, 1996, as the extent to which two stimuli are appropriate for combination in a food product) has been shown to play an important role at both the sub- and supra-threshold levels. More recently, Labbe *et al.* (2006) have shown that odour congruency also plays a role in people's perception of bitterness in real food products such as a cocoa beverage (see also Cliff and Noble, 1990; Schifferstein and Verlegh 1996; Stevenson and Boakes, 2004).

Taken together, the results reported in this section therefore support the view that no matter where you were born (or where you grew up), your brain will use the same rules of multi-sensory integration in order to combine the olfactory and gustatory (and presumably also oral-somatosensory) cues that contribute to the perception of flavour. However, which specific tastants and olfactants (and, as we will see below, colours) are integrated will depend on the particular ingredients that tend to be combined in the particular cuisine that the participant is familiar with. It is interesting to note here that we actually start to learn our preferences for specific flavours while in the womb. In fact, newborns have been shown to express a preference (in terms of preferential head-turning) toward certain odours as a function of the foods consumed by their mothers while they were pregnant (Ganchrow and Mennella, 1990; Schaal *et al.*, 2000).

10.4 ORAL-SOMATOSENSORY CONTRIBUTIONS TO MULTI-SENSORY FLAVOUR PERCEPTION

The oral-somatosensory system plays a crucial role in multi-sensory flavour perception, informing us about the temperature of a food as well as its texture, not to mention the burning sensation associated with eating chilli (see Lawless *et al.*, 1985). Tactile cues play an important role in helping to localise our flavour experiences in the oral cavity (Todrank and Bartoshuk, 1991).

The oral texture (or *mouthfeel*) of food and drink also influences multi-sensory flavour perception (e.g. Bult *et al.*, 2007; Frost and Janhøj, 2007; Weel *et al.*, 2002). While the results of early studies (e.g. Christensen, 1980) led to the suggestion that increased viscosity in a foodstuff gave rise to a reduced perception of taste, it has for many years been difficult to disentangle whether such effects had a physicochemical or psychological origin (since increased viscosity is likely to reduce volatility at the food–air interface; see Delwiche, 2004). However, recent technological advances have meant that it is now much easier to demonstrate the genuinely psychological nature (of at least a part) of this cross-modal effect.

Bult *et al.* (2007), for example, conducted an elegant study in which a creamy odour was presented either orthonasally or retronasally using a computer-controlled olfactometer. At the same time, milk-like foods with different viscosities were delivered to the participant's mouth. The participants had to rate the flavour intensity, as well as the thickness and creaminess of the resulting flavour experience. The key result to emerge from this study was that participants' ratings of flavour intensity decreased as the viscosity of the liquid increased, regardless of whether the odour was presented orthonasally or retronasally. Given the independent control of texture and odour delivery in this study, these results therefore highlight the important role that texture (mouthfeel) plays in multi-sensory flavour perception in humans. Bult *et al.*'s results also suggested that the presence of a retronasal odour could alter the perceived thickness of a foodstuff in the mouth as well (see also Sundqvist *et al.*, 2006; Tournier *et al.*, 2009).

Everyone has heard of the ventriloquist: the illusionist who projects his/her voice to the articulated lips of his/her dummy. This illusion provides an example of the visual capture of perceived auditory location (Alais and Burr, 2004). The evidence now suggests that a very similar effect may also be taking place in our mouths whenever a food or drink is consumed. It turns out that the perceived localisation of a tastant follows the location of a tactile stimulus drawn across the tongue (Green, 2002; Todrank and Bartoshuk, 1991; see also Lim and Green, 2008; the same may also be true for olfactants, Murphy and Cain, 1980). What is more, given the pronounced differences in transduction latencies between the senses, the tactile sensations associated with eating and drinking will normally arrive centrally in the human brain before either the associated gustatory or olfactory stimuli, and hence this 'prior entry' of the tactile signal may also play a role in the combined multi-sensory flavour experience being localised to the mouth as well (see also Kobayakawa *et al.*, 2009; Pfeiffer *et al.*, 2005; Small *et al.*, 2005; von Békésy, 1964).

Another kind of cross-modal interaction involving oral-somatosensation takes place between *temperature* and *taste*. Once again, however, there are marked individual differences: Roughly 33–50% of the population experience what is known as the '*thermal-taste*' illusion (see Cruz and Green, 2000; Green and George, 2004). Green and his colleagues found that by raising or lowering the temperature at various points on people's tongues, they were able to elicit sensations of sweet, sour, salty and bitter – that is four of the basic tastes. Those individuals who experience the thermal-taste illusion also tend to experience other tastes as being more intense as well (Bajec and Pickering, 2008).

Having reviewed the evidence concerning the multi-sensory integration of gustatory, olfactory (both orthonasal and retronasal), and oral-somatosensory cues that *directly* (see Delwiche, 2004; ISO 5492, 1992) contribute to (or influence) the multi-sensory perception of flavour, I will now move on to look at the cross-modal influence of auditory and visual cues to multi-sensory flavour perception.

10.5 AUDITORY CONTRIBUTIONS TO MULTI-SENSORY FLAVOUR PERCEPTION

Try eating a crisp (or potato chip) without making a noise. It's impossible! The question therefore arises as to whether such food-related eating sounds exert any influence on our perception of food. One might wonder, for example, whether crispy or crunchy foods taste different if eaten at a noisy party, say, or whilst listening to loud white noise (if you happen to find yourself in a psychologist's laboratory; e.g. Masuda *et al.*, 2008). In fact, interest in the role of audition in multi-sensory flavour (and texture) perception goes back a long way (see Petit, 1958; Srinivisan, 1955, for early research). However, the majority of published studies have tried to correlate subjective ratings of the crispiness/crunchiness of various foods with objective measures of the sound elicited by biting into, or mechanically crushing, them (see Spence and Zampini, 2006; Vickers, 1991, for reviews). More recently, Zampini and Spence (2004) have demonstrated that the sounds that people make when they bite into dry food products such as crisps (potato chips), contribute as much as 15% to their perception of crispness and/or freshness.

The participants in Zampini and Spence's (2004) study had to bite into nearly 200 Pringles potato chips (all more or less identical in shape, size and weight, and hence ideal for psychophysical investigation), and rate each one in terms of its crispness and freshness using anchored scales. Real-time auditory feedback of the noise made by participants while they were biting into each crisp was played back over closed ear headphones. The participants actually perceived the sounds as coming from the potato chips themselves (i.e. rather than from the headphones) due, presumably, to the audiotactile ventriloquism effect (Caclin *et al.*, 2002). The auditory feedback was sometimes altered in terms of its frequency composition and/or overall loudness. That is, when biting into each potato chip, the sound that participants heard could either be attenuated by 0, 20 or 40 dB across the entire frequency range, or else only those frequencies above 2 kHz could either be boosted or cut (by 12 dB) or left unaltered.

The participants reported that the potato chips tasted both significantly crisper and fresher when the overall sound level was increased and/or when just the high frequency sounds were amplified (see Figure 10.4). By contrast, the participants rated the crisps as being both significantly staler and significantly softer when the overall intensity of the sounds made by their biting into the potato chips was reduced and/or when the high frequency sounds were attenuated. These results therefore highlight the important role that food-eating sounds play in modulating people's perception and evaluation of foods (at least for those foods that make a 'noise' when we bite into them). Subsequently, Zampini and Spence (2005) have gone on to show that people's ratings of the carbonation of fizzy beverages can also be modified by changing the loudness of the popping sounds that they hear when evaluating a beverage presented in a plastic cup.

It should, however, be noted that it is not only the overall loudness or frequency composition of food-eating sounds that modulate the perception of food texture, the temporal qualities of food sounds, such as, for example, how uneven or discontinuous they are, can also influence how 'crispy' people perceive a food to be (e.g. Vickers and Wasserman, 1979), or how carbonated a drink appears to be (Zampini and Spence, 2005). Although beyond the scope of the present review, it is worth bearing in mind that environmental sounds and background music have also been shown to exert a surprisingly large effect on our food-eating and drinking behaviours as well (see Spence and Shankar, 2010, for a review). Spence *et al.* (2011) have even shown that the sound of a product's packaging (i.e.

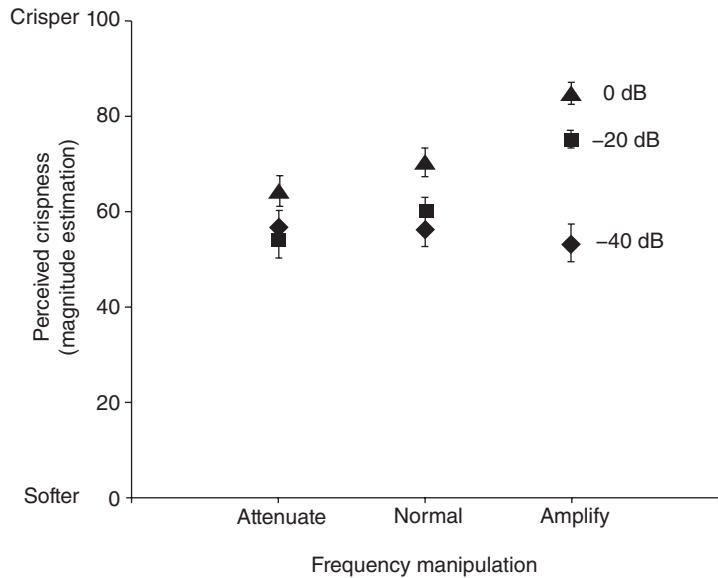


Figure 10.4 Results highlighting the effect of changing the food-eating sounds heard by participants on their multi-sensory perception of the crispness of potato chips (see Zampini and Spence, 2004). Potato chips were judged as crisper (and fresher) when the overall sound level was boosted, and/or when just the high frequency components of the sound (>2 kHz) were amplified. Reproduced from Zampini and Spence 2004, with permission.

the rattling of a noisy crisp packet) can influence people's perception of the crispness of potato chips as well. The available evidence now suggests that environmental sounds can influence our perception of both the sensory-discriminative and the hedonic attributes of food and drink items (see Spence *et al.*, 2011, for a review).

Given the important role that auditory cues have been shown to play in our perception of food and drink, one open question for future research concerns what happens to individuals who are deaf. It is, at present, unclear whether their multi-sensory flavour experiences are similar to those of normal-hearing adults who eat food while listening to loud white noise, say (which masks food sounds; Masuda *et al.*, 2008), or whether instead the relative contribution of each of the residual senses is somewhat different for deaf individuals due to the consequences of cortical plasticity.

10.6 'VISUAL FLAVOUR': VISUAL CONTRIBUTIONS TO MULTI-SENSORY FLAVOUR PERCEPTION

It has been known for many years that visual cues play an important role in multi-sensory flavour perception (Masurovsky, 1939). In fact, more than 100 studies have now been published on this topic since the original report by Moir in 1936 (see Clydesdale, 1993; Spence *et al.*, 2011, for reviews). By and large, the research that has been published to date has shown that people's judgement of the identity of a food's taste, aroma and flavour can all be influenced by changing the colour (either appropriate, inappropriate, or absent) of the foodstuff that people happen to be evaluating. By contrast, studies investigating the

Table 10.1 Summary of the results from Maga's (1974) study highlighting the effect of adding colour on participants' sensitivity to each of the four traditional basic tastants when dissolved in solution (and when compared to performance when the tastants were presented in uncoloured solutions). The table highlights the significant differences resulting from the colouring of the solutions.

Colour of solution	Taste			
	Sour (citric acid)	Sweet (sucrose)	Salt (sodium chloride)	Bitter (caffeine)
Red	No effect	No effect	No effect	Decrease
Yellow	Decrease	Decrease	No effect	No effect
Green	Decrease	Increase	No effect	No effect

effect of varying the intensity of the colour added to a food (typically a coloured beverage) have revealed rather mixed results (see Spence *et al.*, 2011, for a review). As yet, far less research has attempted to investigate the influence of other visual appearance cues, such as opacity etc. on multi-sensory flavour perception (see Hutchings, 1977).

One of the classic studies demonstrating the influence of colour on people's *taste* sensitivity was conducted by Maga (1974). He investigated the consequences on perceptual thresholds for the four basic tastes (e.g. sweet, sour, bitter and salty) of colouring aqueous solutions red, yellow or green. In several cases, Maga observed that the concentration of the tastant had to be increased in order for participants to correctly detect its presence in a coloured, as compared to in an uncoloured, solution. So, for example, the addition of yellow colouring to a sweet solution significantly decreased taste sensitivity while green colour increased it (see Table 10.1). Perhaps surprisingly, the addition of red colouring had no effect on the sweetness threshold (though see also Frank *et al.*, 1989, for similar results). Colouring a solution red resulted in a significant lowering of participants' sensitivity to bitter taste, while the addition of yellow and green colouring had no such effect. With respect to sour taste sensitivity, colouring a solution either yellow or green significantly decreased participants' sensitivity, with red colouring again having no significant effect. Interestingly, taste detection thresholds for the salt solutions were unaffected by colouring, perhaps because salty foods come in so many colours.

More recently, Morrot *et al.*, (2001) investigated the effects of colour on people's perception of wine aroma. They were able to fool more than 50 students enrolled on a university wine degree course in Bordeaux, France into believing that they were holding a glass of red wine, simply by colouring a white Bordeaux wine artificially red with an odourless food dye! The participants in this study were initially given a glass of white wine and instructed to describe its aroma after sniffing it. Next, they were given a glass of red wine and asked to do the same. The students used completely different terms in order to describe the aromas of the two wines – terms like citrus, lychee, straw and lemon in order to describe the white wine and terms such as chocolate, berry, tobacco and so on in order to describe the red wine (see also Ballester *et al.*, 2009). Finally, the students were given a third glass of wine, and were once again asked to describe the aroma. The third glass again looked like another glass of red wine but was, in fact, the same white wine that they had been given originally, but now coloured so as to make it look indistinguishable from a red wine. Surprisingly, the participants now described the wine using red wine odour descriptors again. That is, they apparently no longer perceived any of the aromas in the

coloured wine that they had previously reported when drinking the untainted white wine. This result therefore powerfully demonstrates vision's dominance over orthonasal olfaction (see also Parr *et al.*, 2003).

Moving away from the study of wine, several other studies have demonstrated a similarly profound effect of visual cues on people's olfactory discrimination (Stevenson and Oaten, 2008) and on their identification of both fruit- and non-fruit-flavoured beverages (e.g. Blackwell, 1995; Davis, 1981; Shankar *et al.*, 2010b.; Zellner *et al.*, 1991; Zellner and Durlach, 2003), as well as on their ratings of odour intensity (Zellner and Kautz, 1990; Zellner and Whitten, 1999).

The story regarding vision's influence over odour perception has, however, been complicated somewhat by the results of a study by Koza *et al.* (2005). These researchers demonstrated that colour had a qualitatively different effect on the perception of orthonasally- versus retronasally-presented odours associated with a commercially-available tangerine-pineapple-guava flavoured water drink (see also Christensen, 1983; Zellner and Durlach, 2003). In particular, they found that colouring the solutions red led to odour enhancement in one group of participants when an odour was sniffed orthonasally, while leading to a reduction in perceived odour intensity when it was presented retronasally instead to another group of participants! Koza *et al.* accounted for this surprising pattern of results by suggesting that it may be more important for us to correctly evaluate foods once they have entered our mouths, since they pose a greater risk of poisoning. By contrast, the threat of poisoning from foodstuffs outside the mouth is less severe. It may well be that people simply attend more to stimuli originating from within our bodies as compared to those situated elsewhere (cf. Spence *et al.*, 2001), and that this influenced the pattern of sensory dominance that was observed. Should Koza *et al.*'s important results be replicated (preferably using a within-participants experimental design), it would once again add weight to the argument that qualitatively different patterns of multi-sensory integration/perception can be observed following the presentation of orthonasal as compared to retronasal odours (see also Small *et al.*, 2008).

Given the significant effect that colour has been shown to exert on both taste sensitivity (Maga, 1974) and on various aspects of odour perception (e.g. Blackwell, 1995; Davis, 1981; Koza *et al.*, 2005; Shankar *et al.*, 2010b), it should come as little surprise that colour cues have also been shown to exert a robust effect on people's flavour identification responses. For example, the participants in a classic study by DuBose *et al.* (1980) had to try and identify the flavours of a variety of differently-coloured fruit-flavoured drinks. Certain of the colour-flavour pairings were deemed 'appropriate' (e.g. a cherry-flavoured drink coloured red), whilst others were deemed 'inappropriate' (e.g., as when a lime-flavoured drink was coloured red; though see Shankar *et al.*, 2010a, on the problematic notion of colour 'appropriateness'). DuBose *et al.* (1980) reported that participants misidentified the flavours of a number of the drinks when the colouring was inappropriate. In fact, their incorrect answers often seemed to be driven by the colours of the drinks themselves. That is, participants often made what might be classed as *visual-flavour* responses. So, for example, 26% of the participants reported that a cherry-flavoured drink tasted of lemon/lime when coloured green, as compared to no lime-flavour responses when the drink was coloured red instead (see Table 10.2 for a summary of the results).

Similar results have been reported in a number of other studies over the years (e.g. see Spence *et al.*, 2011, for a recent review). An interesting, and as yet unanswered, question here though, is why only a proportion of participants' responses are seemingly influenced by the changing of the colour of the drinks (as in DuBose *et al.*'s, 1980, study). One recent

Table 10.2 Partial summary of the results from DuBose *et al.*'s (1980; Experiment 2) study, highlighting the profound effect that food colouring can have on participants' flavour identification responses. The participants had to try and identify 16 different sequentially-presented beverages created by fully crossing the factors of flavour (cherry-, orange-, or lime-flavoured, or flavourless) and colour (red, orange, green, colourless). The participants had a checklist of 14 possible responses to choose from when trying to identify each of the drinks (strawberry, raspberry, lemon, lime, grape, apple, cherry, orange, blueberry, lemon-lime, grapefruit, apricot, other, or no flavour). The table highlights the distribution of responses from the three most common flavour responses for the cherry-flavoured drink. The numerical values indicate the percentages of each flavour response for each colour.

Reported flavour	Colour of cherry-flavoured drink			
	RED	ORANGE	GREEN	COLOURLESS
Cherry	70%	41%	33%	37%
Orange	0%	19%	0%	0%
Lime	0%	0%	26%	7%

suggestion has been that people may differ in the degree to which particular colours induce specific flavour expectations (Shankar *et al.*, 2010a; Zampini *et al.*, 2007). It is possible that such individual differences in the flavour expectations that are elicited by particular colours may explain why certain colours appear to have a more pronounced effect on people's flavour identification responses. In this regard, it is interesting to note that people are likely to have shared and strong expectations regarding the kinds of bouquet (flavour) characteristics that are signified by seeing a red wine, hence perhaps explaining why such robust results were reported by Morrot *et al.* (2001) in their study when they coloured a white wine red.

One particularly interesting recent result to have emerged from the study of the visual contributions to flavour perception comes from Zampini *et al.* (2008). They demonstrated that super-tasters show less visual dominance over their perception of flavour than do medium-tasters, who, in turn, show less visual dominance than non-tasters. The participants in their study had to try to identify the flavour of fruit-flavoured drinks presented amongst flavourless drinks. The drinks were coloured red, orange, yellow, grey or else presented as colourless solutions. (Overall, the non-tasters correctly identified 19% of the solutions, the medium-tasters 31%, and the super-tasters 67%.) The results showed that colouring the orange-flavoured solutions orange led to a significant increase in the accuracy of participants' flavour identification responses (see Figure 10.5). Similarly, colouring the blackcurrant-flavoured solutions greyish purple also led to a significant facilitation of performance (note here that many blackcurrant-flavoured products, such as, for example, yoghurt are typically coloured a greyish-purple). What is more, the participants in Zampini *et al.*'s study also rated the congruently-coloured drinks as having a more intense flavour than when presented either with no colour or else with an incongruent colour. By contrast, no such effect of congruent colouring was reported on participants' sourness or sweetness intensity judgements. Interestingly, Zampini *et al.* also found that the addition of colouring had the largest effect (in terms of participants' correctly identifying the flavour) on the performance of the non-tasters, less of an effect on the medium-tasters, and very little effect on the colour identification responses of the super-tasters.

In summary, then, the addition of colour (be it appropriate, inappropriate or absent) has been shown to have a profound effect on people's flavour identification responses. The

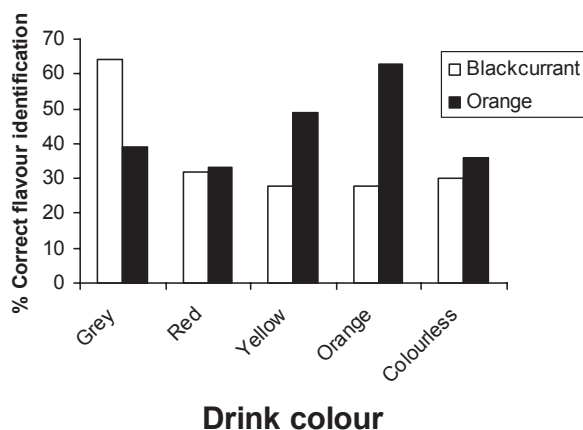


Figure 10.5 The results of Zampini *et al.*'s (2008) study highlighting the influence of colour on people's ability to correctly identify orange- and blackcurrant-flavoured solutions. Reproduced with permission.

manipulation of the *intensity* of the colour added to a foodstuff does not, however, appear to have such a clear-cut effect on people's judgements of flavour (or, for that matter, taste) intensity (Petit *et al.*, 2007; see Spence *et al.*, 2011, for a review). One general point to note here is that if colour's effect on flavour perception is more cognitive in nature than the multi-sensory integration effects that appear to govern oral-somatosensory-gustatory-orthonasal-olfactory interactions (i.e. if it depends on an expectancy set-up by the presence of a particular colour in the substrate), then the exact testing protocol may influence the results of studies in ways that, as yet, have not been fully thought through (see Frank *et al.*, 1989; Spence *et al.*, 2011).

10.7 THE COGNITIVE NEUROSCIENCE OF MULTI-SENSORY FLAVOUR PERCEPTION

The last few years have seen a rapid growth in our understanding of the neural networks that underlie multi-sensory flavour perception. We now know that gustatory stimuli project from the tongue to the primary taste cortex (the anterior insula and the frontal-or-parietal operculum, see Simon *et al.*, 2006), while olfactory stimuli project to the primary olfactory (i.e. piriform) cortex (though see also Johnson *et al.*, 2000; Veldhuizen *et al.* 2009). From there, the inputs from both modalities project to the orbitofrontal cortex (OFC), a small brain structure located behind the eyes. Gustatory stimuli appear to project to caudolateral OFC while olfactory stimuli appear to project to caudomedial OFC. The available evidence currently suggests that the OFC plays a central role in mediating multi-sensory interactions in flavour perception (e.g. Small and Prescott, 2005). In fact, the consensus is currently that the pleasantness (and reward value) of a food (or drink) is represented there (e.g. Rolls and Baylis, 1994; Small, 2004; Small *et al.*, 1997; Small and Prescott, 2005; Small *et al.*, 2001).

The participants in one influential study by de Araujo *et al.* (2003) had to lie in a functional magnetic resonance imaging (fMRI) brain scanner while rating the pleasantness, and congruency, of various different pairings of orthonasal olfactory and gustatory stimuli. The olfactory stimuli were methional (a chicken-broth like odour) and strawberry odour, while

the tastants consisted of sucrose and MSG. The participants were presented with both congruent (e.g. sucrose and strawberry odor) and incongruent (e.g. sucrose and chicken-broth odour) combinations of orthonasal olfactory and gustatory stimuli. Increased neural activity in the OFC was correlated with increased ratings of the pleasantness and congruency of the olfactory-gustatory stimulus pairing that they happened to be evaluating.

In another study, Dana Small and her colleagues presented familiar/unfamiliar combinations of *retronasal* smell and taste stimuli to participants (Small *et al.*, 2004). They observed super-additive neural interactions in the OFC in their event-related fMRI study for familiar (or congruent, sweet-vanilla), but not for unfamiliar (or incongruent) combinations of stimuli (salty-vanilla). Additionally, though, several other areas – including the dorsal insula, frontal operculum and anterior cingulate cortex – also lit-up in what appeared to be a ‘flavour network’ in the human brain. Thus, it appears that familiar combinations of olfactory (both orthonasal and retronasal) and gustatory flavour stimuli lead to enhanced neural responses in those parts of the brain that code for the hedonic (i.e. pleasantness) and reward value of food. Behaviourally, the presentation of familiar (and/or congruent) combinations of stimuli results in the perception of enhanced flavour intensity and increased pleasantness. By contrast, unfamiliar (and/or incongruent) combinations of taste and smell (delivered either orthonasally or retronasally) will likely lead to reduced liking and the *suppression* of neural response in those parts of the brain coding for the intensity and pleasantness of food (De Araujo *et al.*, 2003; Small *et al.*, 2005; see also Skrandies and Reuther, 2008). Indeed, Small *et al.* (1997) reported a significant decrease in regional cerebral blood flow in primary and secondary gustatory cortex and in secondary olfactory cortex during simultaneous presentation of orthonasal olfactory and gustatory stimuli as compared to when they were presented individually.

Oral-somatosensory information regarding food in the mouth is transferred to the brain by means of the trigeminal nerve (V), which projects directly to the primary somatosensory cortex (Simon *et al.*, 2006). This projection carries information concerning touch, texture (mouthfeel), temperature, proprioception, nociception and chemical irritation from the receptors in the mouth. Given what we have seen so far, it should come as little surprise that oral texture (including the perception of fattiness in food) is also represented in the OFC (Eldeghaidy *et al.*, 2011; see also Cerf-Ducastel *et al.*, 2001). Congruent combinations of colour and orthonasally-presented odours have also been shown to lead to enhanced activation in the OFC (Österbauer *et al.*, 2005). As yet though, neuroimaging techniques have not been applied to the case of somatosensory-olfactory interactions (see Stevenson, *in prep.*).

10.8 CONCLUDING REMARKS

Flavour perception is one of the most multi-sensory of our everyday experiences, involving as it does the direct contribution of taste, smell and oral-somatosensory (e.g. mouthfeel and trigeminal stimulation) cues (Small and Prescott, 2005). Auditory and visual cues also influence multi-sensory flavour perception, though they have typically been excluded from traditional definitions of flavour (e.g. Delwiche, 2004; ISO 5492, 1992). I would, however, like to argue that such definitions are overly narrow, and should actually be expanded to include proximal auditory cues elicited by foods in the mouth (and food-eating sounds; see Figure 10.6). The influence of such auditory cues on multi-sensory flavour perception would appear to obey the temporal rule that marks out many effects as reflecting the consequences

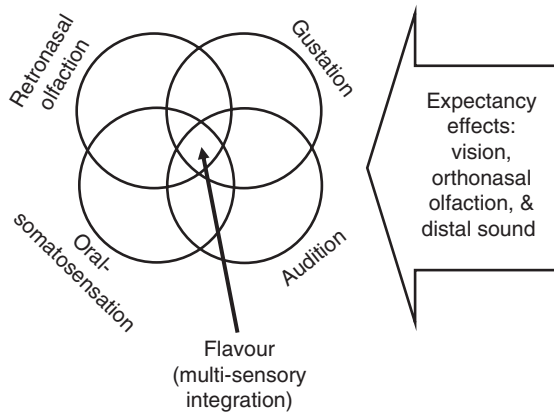


Figure 10.6 Multi-sensory flavour perception – an updated view that incorporates the important role played by food-eating sounds, and which distinguishes between the unique roles that orthonasal and retronasal olfactory cues play in flavour perception. These four interoceptive sensory inputs (that can be linked to consummatory food behaviours; Small *et al.*, 2008) are likely combined through multi-sensory integration to deliver flavour perception. The integration of these cues is disrupted whenever they are desynchronised (e.g. Guest *et al.*, 2002; Pfeifer *et al.*, 2005; Sakai *et al.*, 2001). Exteroceptive cues (namely visual, orthonasal olfactory, and distal auditory) can also influence flavour perception but do so by another mechanism, namely by setting up an expectancy about what the flavour, aroma, and/or taste of a food or drink are likely to be. Expectancy effects are relatively insensitive to the precise synchronisation of the individual inputs, though tend to be larger when the expectancy is set-up prior to tasting than after tasting (see Shankar *et al.*, 2010b). The currently dominant theoretical account of expectancy effects is assimilation/contrast theory (see Shankar *et al.*, 2010b).

of multi-sensory integration rather than some form of expectancy effect (see Guest *et al.*, 2002; Holmes and Spence, 2005; Sakai *et al.*, 2001), which are rarely sensitive to the precise synchronisation of the constituent sensory inputs.

I further believe that it is currently an open question as to whether one should also include exteroceptive cues, such as those provided by the distal sounds associated with foods (e.g. the sizzling steak) or food-preparation, visual appearance cues, and orthonasal olfaction in one's definition of flavour (see also Small *et al.*, 2004). The answer to this latter question may turn on what exactly is meant by the term 'flavour' (see also Auvray and Spence, 2008; Stevenson, 2009). Nevertheless, however one defines the term, the point remains that the human brain appears to effortlessly bind all of the available sensory cues (regardless of their modality of occurrence) into a multi-sensory flavour percept (or Gestalt).

The evidence cited in this review has demonstrated just how important multi-sensory integration is to multi-sensory perception of flavour. That said, it is currently unclear whether the mechanisms underlying cue combination (multi-sensory integration) in the case of multi-sensory flavour perception are necessarily the same as those outlined elsewhere for the combination of auditory, visual and tactile cues in non-food perception (see Ernst and Bühlhoff, 2004; Small, 2004; Stein and Meredith, 1993; Stein and Stanford, 2008). One possibility here is that the interoceptive flavour cues may be combined along similar lines to those observed by Stein and his colleagues at the single-cell level (see also Small *et al.*, 2004), while exteroceptive cues may influence performance by means of expectancy effects instead (see Cardello, 2007; see Deliza and MacFie, 1997; Hutchings, 2003; Shankar *et al.*,

2010b). According to this account, visual appearance cues (especially colour), orthonasal olfactory cues and distal food (and food preparation) sounds set up an expectation regarding the food that is about to be eaten. When the food or drink is then evaluated (in terms of its flavour, aroma or taste), assimilation may occur if the discrepancy between what was expected and what was perceived is small, whereas contrast may occur if the discrepancy between one's expectation and actual interoceptive information is too great. Indeed, the assimilation/contrast model has already been used previously to account for the results of multi-sensory integration on people's hedonic responses to (and perception of) food and drink (Yeomans *et al.*, 2008). There seems no reason why it cannot be extended to the case of people's sensory-discriminative food judgements as well (see Shankar *et al.*, 2010b).

The majority of the research reviewed in this chapter has focused on the sensory-discriminative aspects of multi-sensory flavour perception. Equally important, if currently somewhat less thoroughly studied are, of course, the multi-sensory contributions to people's hedonic responses to food and drink (i.e. how much do they like it). All that there is time to say here is that the available research shows that multi-sensory interactions appear to play just as important a role in people's hedonic responses to food and drink as they do to our sensory-discriminative responses (Yeomans *et al.*, 2008). That said, the results of many cognitive neuroscience studies now converge on the conclusion that the OFC plays a central role in the multi-sensory integration of gustatory, olfactory, tactile and visual (and presumably also auditory) cues (e.g., De Araujo *et al.*, 2003; Österbauer, *et al.*, 2005; Rolls and Baylis, 1994; Small *et al.*, 1997, 2004). The OFC appears to code the reward value of food. However, the OFC should be seen as just one node in a complex 'flavour network' that spans multiple loci in the human brain, including the anterior insula, frontal operculum, anteromedial right temporal lobe, anterior cingulate cortex, posterior parietal cortex and possibly also the ventral lateral prefrontal cortex (Small *et al.*, 2004; Small and Prescott, 2005).

While it has been known for many years that taster status influences the experience of certain bitter tastes (Bartoshuk, 2000), there is now a growing body of evidence to suggest that it also affects people's responses to other tastants (Bajec and Pickering, 2008), as well as their responses to the oral-somatosensory attributes of foods (see Eldeghaidy *et al.*, 2011; Essick *et al.*, 2003; Prescott *et al.*, 2004). The latest evidence has also provided some intriguing preliminary evidence that taster status might influence how much weight people put on what they see when trying to identify a food or drink's flavour as well (Zampini *et al.*, 2008). There is also growing interest in the individual/cultural differences that pervade the field of multi-sensory flavour perception (e.g. Shankar *et al.*, 2010b).

Many of the world's largest food companies and flavour houses are becoming increasingly interested in results such as the reduction in olfactory and gustatory thresholds reported by Dalton *et al.* (2000) and others (e.g., Labbe *et al.*, 2006, 2007; Petit *et al.*, 2007; Pfeiffer *et al.*, 2005), not to mention the experience-dependent (and cross-cultural) differences that have been reported (Spence, 2008). Olfactants are often expensive to produce, whereas tastants (such as sugar) are relatively cheap. Therefore, any means of reducing the amount of odorant needed to deliver a certain flavour or aroma to the consumer can potentially mean a huge saving. Researchers are currently working on ways to reduce the amount of 'harmful' ingredients, such as sugar, salt, fat, carbonic acid and so on in foods (e.g. Lawrence *et al.*, 2009). The hope is that a better understanding of the cognitive neuroscience of multi-sensory flavour perception may help such companies to create foods that are healthier for the consumer while keeping the flavour profile as constant as possible. That

said, it is also important to note that there is still quite a gap between much of the basic laboratory research and the needs of the marketplace (e.g. Garber *et al.*, 2001; Pfeiffer *et al.*, 2005: p. 544; see also Labbe *et al.*, 2006).

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Part Four

Principles and Practices of Instrumental Characterisation for Eating and Sensory Perception Studies

11 'Oral' Rheology

Jason R. Stokes

11.1 INTRODUCTION TO FOOD RHEOLOGY AND ORAL PROCESSING

During oral processing, foods and beverages are subject to a range of mechanical deformation processes. Oral rheology concerns how food flows and moves around the oral cavity, the amount of force required to bite the food material, the amount of chews required to obtain optimum consistency for swallowing, the rate of transfer of taste and aroma components to chemoreceptors on the tongue and retronasal cavity respectively, and the mechano-sensation arising from the resistance to shear imposed by the tongue. However, food responds to shear in a very complex and non-linear manner, and will often exhibit mechanical characteristics of both solids and liquids. In addition, masticated food mixes with saliva that is continually being generated in the oral cavity due to mechanical and chemical stimuli. It is thus expected that the rheological properties of the comminuted food–saliva mixture (i.e. bolus) becomes increasingly important during oral processing of foods. It is thus very difficult to predict how food will behave in the mouth during the eating process or how its rheological properties affect sensory perception. This chapter provides a brief summary of key fundamental rheological concepts, which provides a basis for beginning to understand how rheology affects the dynamics of foods and beverages during oral processing.

Rheology is the study of the deformation and flow of matter. To begin to understand rheology, it is necessary to consider first the theories of Isaac Newton on the flow of liquids and Robert Hooke on deformation of solids (Barnes *et al.*, 1989). Under simple shear of a fluid between two plates, as shown in Figure 11.1(a), the shear stress (σ) within simple fluids is directly proportionally to the velocity gradient, $\dot{\gamma} = \frac{\partial v_x}{\partial y}$. This is known as Newton's law of viscosity:

$$\sigma = \eta \dot{\gamma} \quad (11.1)$$

$\dot{\gamma}$ is the shear rate and the constant of proportionality, η , is the viscosity. This is the simplest constitutive model describing the flow properties of fluids and is applicable for most gases

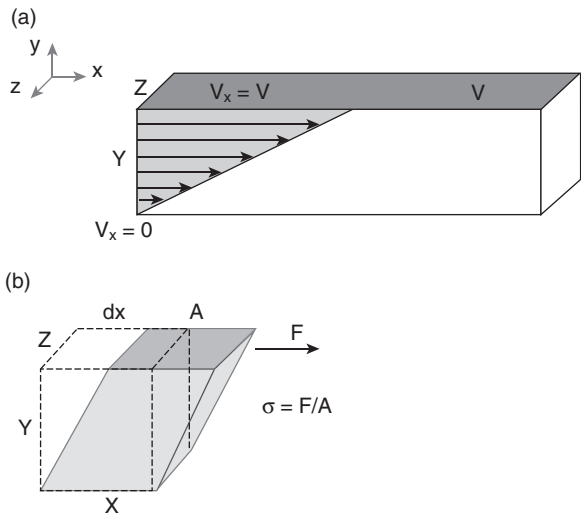


Figure 11.1 Schematic of deformation process for liquids and solids. (a) Liquid between two plates, where the top plate is set into motion by applying a force to move so it moves at a constant velocity, V . (b) Elastic solid material deformed by an applied force, F .

and simple fluids such as water, soft drink, milk and glucose syrup. When a purely elastic ‘Hookean’ solid is deformed by an applied shear stress, it reaches a deformed state as shown in Figure 11.1(b) that remains until the stress is removed. This is defined by Hooke’s law for purely elastic solids:

$$\sigma = G\gamma \quad (11.2)$$

γ is the strain, $\gamma = \frac{dx}{y}$, and G is the rigidity or shear modulus. Both constitutive models are linear models that assume direct proportionality of the shear stress with either strain rate or strain, respectively.

Most fluids and soft solids do not obey these simple linear models and are said to be non-Newtonian, examples of which are: yoghurt, mayonnaise, ice cream, chocolate, cheese, mash potato, custard, dough, sauces, crushed tomatoes, fruit nectar and some juices, cream, jelly, salad dressing, some flavoured milks, thick shakes, marshmallows, margarine, butter and so on. The non-Newtonian nature of these materials is usually obvious. For example: mayonnaise holds its shape like a solid when sitting on a plate, yet it spreads easily with a knife as if it was a liquid; salad dressing pours like a low viscosity liquid, yet its ability to suspend herbs and oil droplets without them settling or floating is characteristic of a high viscosity fluid or even a solid; tomato ketchup flows much more readily following a good shake of the sauce bottle. The viscosity of food materials is typically dependent on the shear rate applied to it, the duration of the shear, and any prior shear and thermal history.

Non-Newtonian food materials are usually ‘viscoelastic’ since they possess both solid-like and liquid-like properties that depend on the time scale of the deformation process. A concept that has arisen in the field is that everything flows if you wait long enough, which is captured by the Deborah number (Barnes *et al.*, 1989):

$$De = \lambda/\tau \quad (11.3)$$

τ is the characteristic time of the deformation process (e.g. $1/\dot{\gamma}$) and λ is the characteristic time of the fluid, for example zero for a Newtonian fluid and infinite for a Hookean elastic solid. Thus a high Deborah number corresponds to solid-like behaviour while a low Deborah number corresponds to liquid-like behaviour.

11.2 LIQUID FOOD RHEOLOGY AND STRUCTURE

11.2.1 Dispersions of particles and polymers

Considering fluid foods as dispersions of particles or polymers is a starting point when considering the origin of the rheology of liquid foods. The viscosity of liquid foods is determined by the viscosity of the solvent phase, which in most cases is water, and the amount of dispersed non-colloidal and/or colloidal ($<1\mu\text{m}$ particle size) entities present including oil droplets, bubbles, starch granules, plant fibres and protein micelles (e.g. casein micelles in milk). In the limit of low shear rates and at very dilute concentrations, the viscosity of spherical particles suspended in a liquid medium follows Einstein's equation:

$$\eta = \eta_s(1 + 2.5\phi) \quad (11.4)$$

η_s is the solvent viscosity and ϕ is the phase volume of dispersed spheres. Einstein's equation arises from considering that there is an increase in the path length for a fluid element to travel around the dispersed object along a flow streamline. It is found that Einstein's equation can be used for any dispersed system at very dilute concentrations. However, while for non-porous hard spheres the phase volume is directly measurable, this is not the case for most dispersed components that incorporate solvent into their structure (e.g. hydrogel particles, swollen starch granules, plant cells), and polymers that are subject to thermal fluctuations from Brownian motion. In such cases, the intrinsic increase in viscosity from the dispersed phase is given in terms of concentration:

$$\eta = \eta_s(1 + [\eta]c) \quad (11.5)$$

$[\eta]$ is the intrinsic viscosity with the unit of inverse concentration. $[\eta]c$ corresponds to the effective increase in viscosity due to the inherent presence of the dispersed entity. Beyond 2–5% phase volume, deviations from Einstein's equation occur primarily from hydrodynamic interactions with neighbouring particles, and further increases in viscosity depend on the particular dispersed phase and how it responds to an applied flow.

For dispersions of spherical hard spheres, Einstein's equation can be expanded to account for hydrodynamic effects and free volume as concentration is increased (Ball and Richmond, 1980). This leads to the derivation of the Kreiger–Dougherty equation (Kreiger and Dougherty, 1959) that gives the viscosity as a function of phase volume up to a maximum packing fraction (ϕ_m):

$$\eta = \eta_s \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta_0]\phi_m} \quad (11.6)$$

ϕ_m corresponds to the phase volume when the viscosity approaches infinity. For hard spheres, $\phi_m \sim 0.64$ which matches that required for random close packing and $[\eta_0]$ is the intrinsic viscosity based on volume fraction so that $[\eta_0] = 2.5$. However, values in the range of $\phi_m \sim 0.60$ – 0.64 and $[\eta_0] \sim 2.5$ – 3.2 have been used to fit to experimental data (Barnes *et al.*, 1989). It is also common for the product of $[\eta_0]\phi_m$ to equal 2 (Quemada, 1978).

While both Einstein's equation and the Kreiger–Dougherty equation are derived for hard spheres, in the limit of low shear rates they are also used to describe the viscosity of other dispersed entities such as anisotropic particles and soft particles including colloids, microgels, emulsion droplets, protein micelles (e.g. milk), starches and bubbles. This is achieved by fitting values of ϕ_m and $[\eta]$ to experimental data. For soft particles or droplets, $\phi_m > 0.64$ because the particles deform and/or deswell to accommodate the presence of their nearest neighbours (Stokes, 2011; Adams *et al.*, 2004). For anisotropic particles, $\phi_m < 0.64$ and ϕ_m decreases with increasing aspect ratio (Barnes *et al.*, 1989). Anisotropic particles have a higher viscosity than spherical particles at the same volume fraction, and the intrinsic viscosity has been empirically found to depend on aspect ratio (Barnes *et al.*, 1989). However, anisotropic particles are also susceptible to orientate under low amounts of shear, which leads to a greater degree of shear thinning compared to spherical particles. Figure 11.2(a) shows a comparison between the zero-shear viscosity for hard and soft spheres, as well as anisotropic particles and linear polymers as a function of effective phase volume. Effective phase volume is the phase volume determined from the size of a dispersed entity under dilute solution conditions.

The viscosity of polymer solutions depends on the relative concentration of the dispersed macromolecules, its conformation in the solvent and any interactions between polymer

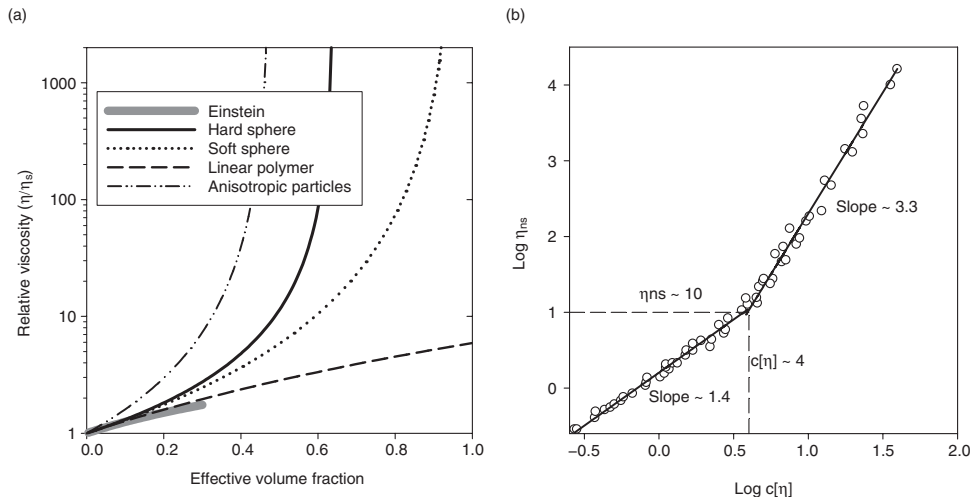


Figure 11.2 Zero-shear viscosity as a function of the effective phase volume of dispersed phase for particles and polymer, showing: (a) relative viscosity (η_0/η_s) for typical hard and soft spheres, as well as anisotropic particles using equation (11.6) in comparison to a linear polymer (adapted from (Stokes, 2011)), (b) Specific viscosity ($(\eta_0/\eta_s) - 1$) for various polysaccharide solutions including dextran, carboxymethylcellulose, alginate, carrageenan and hyaluronate. Reproduced from Morris *et al.*, 1981, pp. 5–21, with permission from Elsevier.

chains. Many polymers are in a disordered random coil conformation whose shape continually fluctuates due to Brownian motion (Ferry, 1980). As for other dispersed entities, $[\eta]$ is a characteristic property of an isolated polymer and represents a measure of its hydrodynamic volume in a given solvent as calculated at the limit of dilute concentrations using Equation 11.5. The hydrodynamic resistance is determined by a balance between hydrodynamics and the Brownian randomising forces. While most polymers are considered to occupy a spherical shape, under shear they can orientate, unravel and/or elastically deform. Hence it is generally necessary to evaluate $[\eta]$ at the low shear rate limit to minimise such complications. The intrinsic viscosity is directly related to molecular dimensions, and various models are available that relate intrinsic viscosity to the macromolecule's radius of gyration and shape. An empirical power-law equation is also used to describe the relationship between $[\eta]$ and molecular weight, the Mark–Houwink equation: $[\eta] = K.M^a$. The values of K have been tabulated for many food macromolecules in (Lapasin and Prici, 1995).

Polymer solutions are normally classified into three regimes of concentration. The dilute regime corresponds to when polymer chains are not in contact, which is the case when $C < C^*$ where C^* is the overlap concentration. The semi-dilute regime occurs when coils begin to interact, and this is denoted by a sharp increase in slope of the viscosity against C (see Figure 11.2b). At higher concentrations, entanglements occur and there is another transition in viscosity dependence on concentration (concentrated regime). Polysaccharides are the main polymeric component within most foods, and these can be found to range from having flexible random coil (e.g. guar gum) to rigid rod (e.g. xanthan gum) conformations (Lapasin and Prici, 1995; Robinson *et al.*, 1982). Figure 11.2(b) shows a typical plot of the specific viscosity ($\eta_{sp} = \frac{\eta_0}{\eta_s} - 1$) and concentration (C) showing the transition between the dilute and semi-dilute regime for disordered polysaccharides (Morris *et al.*, 1981). These regimes are described by a power-law model:

$$\eta_{sp} = a.C^b \quad (11.7)$$

For polysaccharides: $1 < b < 1.6$ in the dilute regime, and $1.9 < b < 5.6$ for the semi-dilute regime, while C^* varies from $1/[\eta]$ to $4/[\eta]$ (Lapasin and Prici, 1995).

It should be emphasised that fluid foods contain a range of components that will all contribute to the rheology in different ways, and more detailed insights will usually be required to develop appropriate relationships between rheology and structure. However, a first approach to understanding the origin of a food's rheology is by considering its dispersed components as particles and/or polymers.

11.2.2 Shear thinning

The flow behaviour of fluid foods can usually be described by plotting the shear stress against shear rate, as shown in Figure 11.3. A linear relationship that passes through the origin indicates it is a Newtonian fluid. Newtonian fluid foods are those that contain low molecular weight molecules such as sugar and low phase volumes of dispersed components such as polymers or solids; examples include water, most sugar syrups and honey, oils, filtered juice, milk and most low viscosity carbonated beverages (Rao, 2007). However, the presence of macromolecules and moderate concentrations of dispersed solids (particularly colloids and anisotropic particles such as plant fibres) can give rise to non-Newtonian

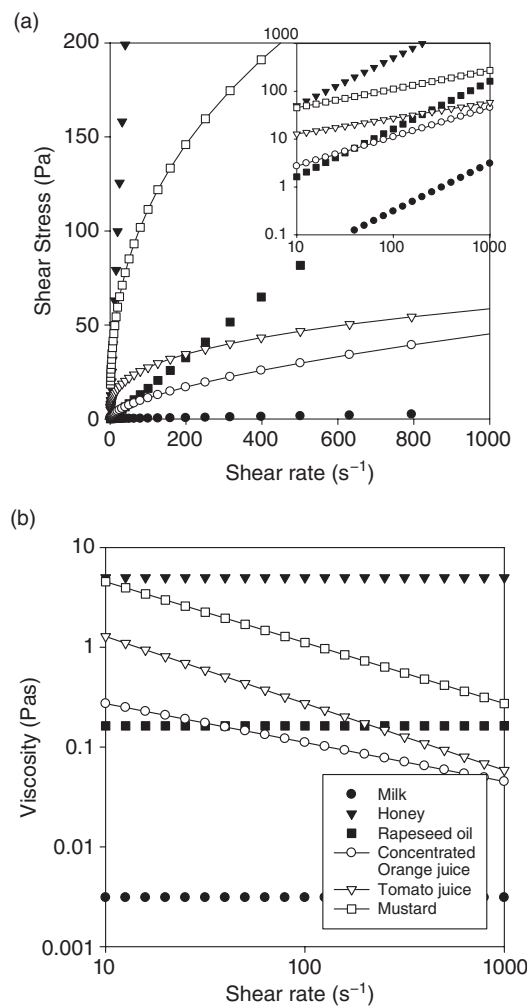


Figure 11.3 Examples on the rheology of shear thinning fluid foods (orange juice, tomato juice, mustard) in comparison to Newtonian fluids (milk, honey, cooking oil): (a) stress versus shear rate (insert shows log scale), (b) apparent viscosity versus shear rate (log scales). Data obtained using power law model parameters listed for numerous foods and beverages in Rao (2007).

behaviour under shear, most notably shear-thinning. Examples of shear-thinning fluid foods are flavoured milks, concentrated fruit juice and salad dressings. Shear-thinning arises due to a change in structure within the fluid due to the flow field, including deformation and alignment of polymeric molecules, movement and reordering of particles, and breakdown of aggregates due to shear.

Shear-thinning is an important property of fluid foods. This exemplified in Figure 11.3 which shows a few examples of the shear stress – shear rate and viscosity – shear rate relationships for a few fluid foods alongside Newtonian liquids. At low shear rates the viscosity of the non-Newtonian food can be greater than that of honey, however, the viscosity can drop considerably upon shear so that it pours and flow easily. There are a multitude

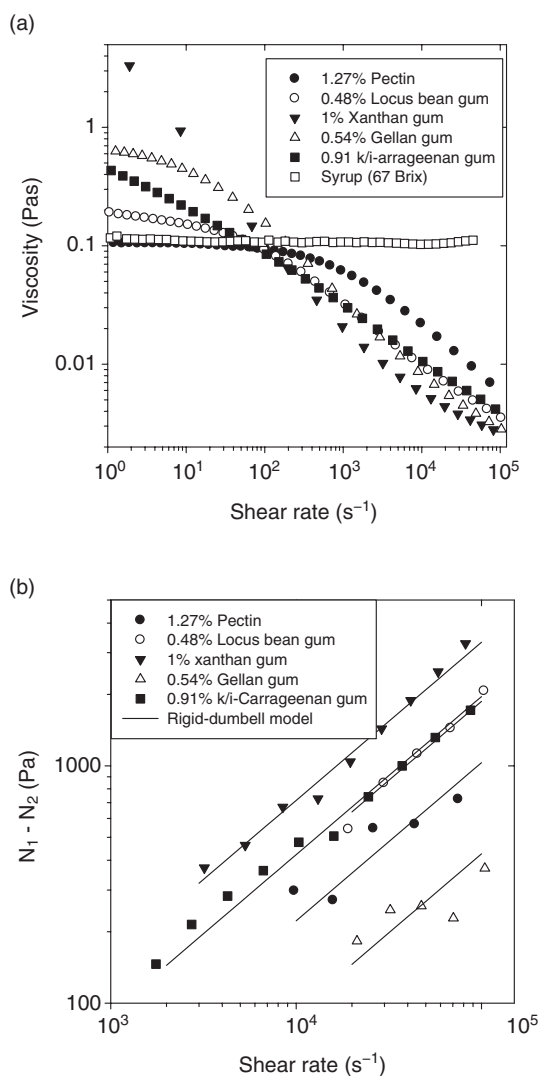


Figure 11.4 Rheology of several polysaccharide solutions that are viscosity matched at shear rates around $50\text{--}100\text{ s}^{-1}$, measured using a narrow gap parallel plate. (a) Apparent viscosity as a function of shear rates across 5 orders of magnitude. (b) Normal stress differences ($N_1 - N_2$) with fits to the rigid dumbbell model assuming $N_2 = 0$. Reprinted with permission from *Langmuir*, Stokes *et al.*, copyright 2011 American Chemical Society.

of thickening agents for foods and beverages on the market, and while the levels of different thickening agents can be varied to obtain fluids with a matched viscosity at a specific shear rate, the viscosity may vary quite a lot above and below this value. Figure 11.4(a) shows this behaviour for several polysaccharides solutions that have the same viscosity at shear rates around $50\text{--}100\text{ s}^{-1}$, but vary considerably above and below this range.

To begin to understand the fundamental origin of shear-thinning, we consider here colloidal hard spheres and polymer solutions. The viscosity of colloidal spheres typically

becomes sensitive to shear rate at $\phi \geq 0.3$. The two essential forces acting on a particle of colloidal dimensions (i.e. particle radius, $r_p < \sim 1 \mu\text{m}$) are viscous forces ($6\pi\eta_s r_p^3 \dot{\gamma}$) and those arising from thermal or Brownian force ($k_b T$). This balance is defined by the Peclet number in Equation 11.8, which excludes the factor of 6π (Larson, 1999). When the viscous force exceeds the Brownian forces ($Pe \gg 1$), the structure can be displaced from equilibrium and interparticle hydrodynamic forces dominates the suspension rheology; this effect leads to shear-thinning for suspensions of colloidal hard spheres (Russel and Sperry, 1994). However, when $Pe \ll 1$, shear induced perturbations to the equilibrium state are restored by Brownian forces on the time scale of the shear flow.

$$Pe = \frac{\eta_s r_p^3 \dot{\gamma}}{k_b T} \quad (11.8)$$

k_b is the Boltzmann constant and T is the absolute temperature. Pe is commonly used as a generalised shear rate to understand the origin for shear-thinning for colloidal and non-colloidal particles. This is achieved by plotting a relative viscosity against Pe for dispersions at different phase volume, temperature, etc. An alternative understanding of Pe is to consider it in terms of a ratio of time scales for the time required for a colloid to diffuse a distance equal to its radius ($\lambda = k_b T / 6\pi\eta_s r_p^3$) and the shearing time scale that is inverse shear rate (Chen *et al.*, 2010; Larson, 1999); in this way it is essentially the same as a Deborah number. Examples where this approach has been used for colloidal spheres are in (Choi and Krieger, 1986; Mewis *et al.*, 1989). For anisotropic particles, such as spheroids, the rate at which a particle reorients by Brownian motion is given by a rotational diffusion coefficient that is dependent on the aspect ratio (Larson, 1999).

In a very similar approach, shear-thinning for polymer solutions is considered to arise when the shear flow is too rapid for the polymer to relax back to its equilibrium conformation. A generalised shear rate is considered to be the ratio of the relaxation time (λ) of a polymer molecule and the shearing process time scale ($1/\dot{\gamma}$). The generalised relaxation time is typically determined from molecular bead-spring models according to the material's intrinsic viscosity and molecular weight (Ferry, 1980):

$$\lambda = \eta_s [\eta] M / RT \quad (11.9)$$

For finite concentration, if $[\eta]$ is unknown then it may be substituted accordingly to obtain $\lambda = (\eta_0 - \eta_s) M / cRT$. Plotting the relative viscosity against $\lambda \dot{\gamma}$ can lead to a single curve across a range of concentrations including the dilute and semi-dilute regimes; as an example, this approach has been applied to xanthan gum (Chen *et al.*, 2010) and guar gum (Robinson *et al.*, 1982) polysaccharide solutions.

11.2.3 Viscoelasticity

The term 'viscoelastic' is used to describe the simultaneous existence of both viscous and elastic properties in a material. As highlighted previously, the degree of viscoelasticity exhibited by non-Newtonian fluid foods and its importance will depend on the time scale and type of deformation applied. In this section, we consider three areas of viscoelasticity: linear viscoelasticity, non-linear viscoelasticity (normal stresses) and extensional viscosity.

11.2.3.1 Linear viscoelasticity

The linear viscoelastic properties are the solid and liquid-like response of the material when the applied deformation is small enough that the stress is linear with strain, and the energy lost in the system is fully recoverable (Ferry, 1980). As noted by the Deborah number, any material at a low enough frequency (long time scale) is expected to behave as a liquid while at a high frequency (short time scale) it may be expected to behave as a solid. These properties have the potential to be directly related to the molecular structure of materials. Characterising linear viscoelasticity can be a convenient and simple method for quality control purposes, while it is non-destructive provided only the linear regime is probed. Linear viscoelastic properties have also been related for some material systems to non-linear rheological properties including viscosity and normal stress differences (Larson, 1999; Stokes and Frith, 2008; Lapasin and Prich, 1995).

Small-amplitude oscillatory shear (SAOS) is the principal technique used to determine the linear viscoelasticity of liquid and soft-solid foods. The response of the system is determined in terms of two stress components: an elastic component that oscillates in-phase with the strain and a viscous component that is 90° out-of-phase with the strain. For viscoelastic fluids, the phase lag or phase angle (δ) is in between these two extremes of an elastic solid ($\delta = 0$) and liquid ($\delta = 90^\circ$), and the resultant stress is expressed in terms of an elastic 'storage modulus' (G') and a viscous 'loss modulus' (G''). A food system is deemed to be 'solid-like' if $G' > G''$, while it is said to be 'liquid-like' when $G' < G''$. The storage modulus as a function of frequency is schematically shown in Figure 11.5 for ideal elastic fluids. Curve A shows the ideal response of a dilute polymer solution that is described by a single relaxation time ($\lambda = G'/\eta_0\omega^2$) (Ferry, 1980; Stokes *et al.*, 2001a). Curve B incorporates multiple relaxation times, which arise for polymer solutions with polydisperse molecular weights (Dealy and Larson, 2006) or mixed polymer blends including phase separated biopolymer solutions (Stokes *et al.*, 2001c). Curve C shows G' to be constant with

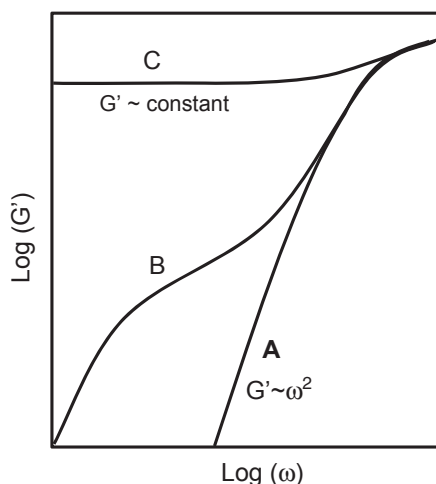


Figure 11.5 Schematic to highlight the dependency of storage modulus with frequency over a typical measurement range on a rheometer, showing (A) ideal elastic fluids such as dilute monodisperse polymer solutions, (B) elastic fluids with multiple relaxation times, and (C) soft materials such as gels and soft glasses. Adapted from Dealy and Larson, 2006, Ferry, 1980.

frequency, which corresponds to soft-solid materials such as polymeric or particulate gels and glasses that are considered in Section 11.3.

11.2.3.2 Non-linear viscoelasticity: normal stresses

The viscosity as a function of shear rate is only one of the material functions required for describing the flow behaviour of non-Newtonian fluids (Barnes *et al.*, 1989). While the viscosity accounts for the response of the material in the direction of the applied shear stress, a small volume element of fluid is also subject to other stresses from the surrounding medium. For an incompressible Newtonian fluid, the normal stresses on a volume element are equal in all directions and equal to the isotropic pressure. Normal stress differences are usually examined in order to eliminate the need to consider the isotropic pressure (Barnes *et al.*, 1989):

$$N_1 = \sigma_{xx} - \sigma_{yy} \quad (11.10)$$

$$N_2 = \sigma_{yy} - \sigma_{zz} \quad (11.11)$$

N_1 is the first or primary normal stress difference and N_2 is the second normal stress difference, and σ_{xx} , σ_{yy} and σ_{zz} are the normal stresses on a small volume element of fluid. For elastic fluids, unequal normal stresses arise in a flow due to the microstructure of the liquid becoming anisotropic. For example, polymer molecules and emulsion droplets occupy a spherical shape at rest, while upon shear their shapes deform to an anisotropic structure. The restoring forces will thus be uneven in the different normal directions and subsequently the normal stress differences can have finite values.

Normal stress differences are inherently a non-linear effect (Barnes *et al.*, 1989). At small shear rates and within the linear regimes of SAOS, the three normal stress components have the same value and are equal to the ambient pressure. It is only when the shear rate is increased that the normal stress differences appear. A power-law relationship is generally observed between N_1 and shear rate that depends on the particular material system. For ideal flexible polymers, a quadratic relationship is expected and often observed for N_1 at low shear rates with a linear relationship observed at high shear rates (Stokes *et al.*, 2001b). When a quadratic response is observed, the relaxation time for the flexible polymer is given by $\lambda = N_1/2\eta_0\dot{\gamma}^2$, which in the limit of low shear rates and frequencies is equivalent to $\lambda = G'/\eta_0\omega^2$. However for polysaccharides that can assume a more rigid and semi-rigid conformation under shear, the power-law index has been observed to be around 2/3 at high shear rates as shown in Figure 11.4(b) (Stokes *et al.*, 2011); this relationship follows a rigid dumbbell model, $N_1 = 1.2nk_bT(\lambda_d\dot{\gamma})^{2/3}$, where n is the number density of molecules and λ_d is the rigid dumbbell relaxation time. Figure 11.4(b) shows the normal stress differences for the polysaccharide solutions discussed previously, which further indicates that while it is possible to match a viscosity at a single shear rate, viscoelasticity can vary dramatically between samples.

The most obvious example of elastic stresses affecting flow behaviour is the rod-climbing effect that is commonly observed when mixing vegetable gums into water and during mixing of dough. During a rotational primary flow, centrifugal forces drive a secondary flow away from the edge of the impellor, up the side walls and down the central shaft which creates a downward vortex (Boger and Walters, 1993). However, polymers in elastic

fluids stretch along the curvilinear streamline and create additional stresses as they attempt to relax against the flow direction. This creates uneven normal stresses and a force directed inwards against the centrifugal force, which subsequently drives the fluid up the shaft in the opposite direction to purely Newtonian fluids. Fluid elasticity can lead to flow instabilities at very low Reynolds numbers, and while this may improve mixing efficiency at low energy consumption with so-called elastic turbulence (Stokes and Boger, 2000), such instabilities can also cause various processing issues that compromise product quality.

11.2.3.3 *Extensional viscosity*

Elastic fluids also show remarkable flow behaviour when subjected to extensional flow conditions, and can possess viscosities in extension that are orders of magnitude greater than their viscosity in shear flow. The most obvious example of the difference in material properties under shear or elongation is highlighted by saliva. Saliva is a shear-thinning fluid, but at moderate shear rates the viscosity is surprisingly not too dissimilar to water (Stokes and Davies, 2007). However, we have all had the experience of a long filament of saliva extending from one's mouth to a piece of food or utensil that has just been in our mouths. The extensional nature of saliva can also be observed by extending a thread between the thumb and forefinger; this thread can last for several seconds while no thread is formed if the same procedure is performed with water. While the shear viscosity of saliva is not too dissimilar to water, its viscosity under elongation is several orders of magnitude larger than water. And while saliva is shear-thinning, it is tension-thickening under elongation that is common for many flexible polymer solutions. For flexible polymers, tension-thickening is considered to arise from unravelling and alignment of the macromolecule in pure extensional flows. However, for many food polymers that have semi-rigid conformation such as xanthan gum, alignment of the macromolecule occurs in the extension flow and a constant extensional viscosity is often observed (Stokes *et al.*, 2001b; Stokes *et al.*, 2001a). Dough (Dobraszczyk and Morgenstern, 2003) and molten cheese (Mitsoulis and Hatzikiriakos, 2009) essentially have the extensional characteristics of molten polymers.

11.2.4 Instrumentation for liquid foods

We introduce a few of the key techniques and pitfalls in rheometry for characterising the shear rheology of fluid foods. Detailed information can be obtained elsewhere (Barnes *et al.*, 1989; Macosko, 1994).

11.2.4.1 *Cone-and-plate*

The cone-and-plate geometry consists of the test fluid confined between a narrow angled cone top plate and a flat bottom plate. This is an ideal geometry because the shear rate and shear stress are not dependent on the radius of the plates. Constant strain rheometers apply a rotation to the bottom plate and measure the torque at the top plate, while constant stress rheometers apply a torque to the top plate while measuring its rotation rate. Many rheometers are equipped with the ability to measure the normal force generated at either the top or bottom plate. For the cone-and-plate configuration, N_1 is equal to the normal force divided by the area of the two confining surfaces. The cone-and-plate is an ideal geometry

for fluids that have moderate levels of shear-thinning, such as hydrocolloids solutions and dilute or semi-dilute colloidal dispersions.

11.2.4.2 *Parallel plate*

The parallel plate geometry consists of two plates separated by a finite distance specified by the user. The major pitfall of the parallel plate is that the shear rate varies from being zero in the middle to a maximum value at the outside rim. This means that for non-Newtonian fluids there is a distribution of viscosity values with the radius of the plate, which makes it difficult to resolve the viscosity at a particular shear rate. While the parallel plate is thus not an ideal geometry, it is still a very useful geometry under many circumstances and, if analysed correctly, the viscosity can actually be resolved with only small degrees of error (Davies and Stokes, 2005; Davies and Stokes, 2008). For fluid foods, it can be used to characterise the rheology using very narrow gaps to extend the shear rate range over that obtained with a cone-and-plate by two orders of magnitude to 10^5 s^{-1} . In addition, narrow gaps can be used to characterise the rheology of fluids using less than $100 \mu\text{L}$. However, care should be exercised when there are suspended particles in the fluid, and measurement artefacts will occur if the gap between the plates is less than about 10 particle diameters. The normal force from the parallel plate is directly related to $N_1 - N_2$. If a sample is characterised using both the parallel plate and cone-and-plate geometry, then both N_1 and N_2 can be obtained.

11.2.4.3 *Concentric cylinder*

The concentric cylinder (i.e. cup and bob) is a standard geometric configuration whereby, provided the gap between the cylinder and wall is narrow, simple shear flow is present between the surfaces. However, unlike the cone-and-plate it is not possible to obtain normal force measurements. Like the cone and plate, the cup-and-bob is ideal for characterising the shear dependence of the viscosity for moderately shear-thinning fluids and simple liquids.

11.2.4.4 *Extensional viscosity*

Extensional flow occurs during manufacturing whenever there is a sudden change in flow geometry, such as during a sudden contraction. It also occurs at the end-use of foods during human manipulation, such as from sucking a beverage through a straw, spreading of jam or butter on bread, and potentially during oral processing and swallowing (Chen and Lolivret, 2011; Padmanabhan, 1995). However, despite its potential importance there are few studies that measure the extensional flow properties of liquid foods. The main reason for this has been the scarcity of commercial equipment available for its measurement due to the difficulty in generating controlled or pure extensional flows for rheological measurements (Padmanabhan, 1995). The lack of a standard technique was highlighted in a study that compared numerous extensional rheology measurements in laboratories around the world on the same model elastic fluid, and it was found that differences in extensional viscosity as a function of extensional strain varied by several orders of magnitude! (Petrie, 2006). The only commercial device currently available that is suitable for liquid foods is the capillary breakup extensional rheometer (CaBER) (Rodd *et al.*, 2005). This involves quickly stretching a fluid sample between two plates, which imposes an extensional strain

on the sample. After cessation of the stretch, the fluid filament gradually thins as a function of time that is related to the extensional viscosity of the sample. Other extensional flow devices that may be useful in the study of liquid foods are the filament stretching device (Tirtaatmadja and Sridhar, 1993), convergent or contraction flows (Petrie, 2006), and squeeze flow (Engmann *et al.*, 2005).

During oral processing, a recent study has indicated that extensional flow may be present during the swallowing action, and a correlation was considered to be present between 'difficulty of swallowing' and the 'stretchability' of the food bolus (Chen and Lolivret, 2011). Easily stretched fluid foods (low extensional viscosity) are thought to require a short residence time before swallowing, while a fluid that is highly resistant to being stretched (high extensional viscosity) requires an extended oral residence time and increases the difficulty of swallowing. This highlights that extensional properties of food are potentially important in the mouth, and further work is needed to understand the role of food extensional properties on their behaviour during oral processing.

11.3 SOFT FOOD RHEOLOGY AND MICROSTRUCTURE

Many foods can be categorised as soft solids, semi-solids or highly-structured fluids. Foods in this category display solid-like properties, but they are distinctly more deformable and liquid-like compared to traditional materials such as plastics and metals (Stokes and Frith, 2008). At the limit of small deformations and stresses, $G' > G''$ and G' is effectively constant in the measurable frequency window of 0.1 – 10 rad/s. Appreciable flow only occurs when a shear stress above a critical value is applied; the critical value is referred to as the yield stress. The yield stress in soft foods is able to suspend dispersed components such as particles, oil droplets and/or air without them settling or creaming. A variety of structuring or thickening agents are often used to ensure long-term stability under a variety of environmental conditions, including variations in temperature and pressure that occur during transport and long-term storage. These thickening agents include polysaccharides, proteins, plant cells, ice crystals, fat crystals, colloids, surfactant vesicles and micelles (and/or various combinations of these) (Stokes and Frith, 2008). In foods, water is the medium that is most commonly thickened to a solid-like state.

11.3.1 Microstructure: gels and glasses

While the list of ways in which to structure fluids is diverse, there are several rheological features that are universal and a simplified approach can be used to understand complex microstructures. From a soft condensed matter viewpoint, soft foods may be categorised as either a *soft-glass* or *gel*, as shown in Figure 11.6 (Stokes and Frith, 2008; Mezzenga *et al.*, 2005). A *gel* arises primarily from attractive interaction and/or the formation of junctions between constituents that consequentially form a percolating network structure at relatively low volume fractions. For example, polysaccharides physically associate to form a polymer network structure, while proteins can behave as colloidal spheres that aggregate due to attractive surface forces (Clark and Farrer, 1995; Clark *et al.*, 2001). A *soft-glass* state occurs at high phase volumes where 'soft' particles are in close proximity to each other such that a disordered solid phase is formed. This phase is considered to be in a dynamically arrested or jammed state at small deformations (Stokes and Frith, 2008). Particle softness arises from their deformable nature (e.g. microgels, plant cells, gelatinised

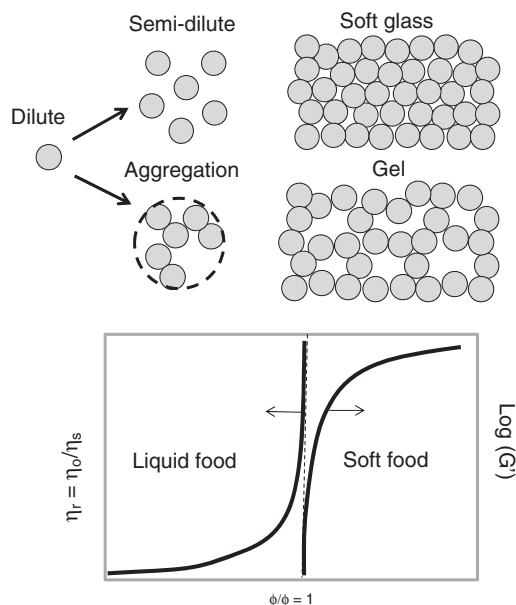


Figure 11.6 General cartoon of the transition from liquid to soft food microstructure, and corresponding relative viscosity and storage modulus with increasing phase volume from left to right. The elasticity for a soft-glass arises from particles being in a jammed state, while for a gel it arises from a percolated network structure from attractive interactions between a dispersed phase. $\phi_m \sim 0.6$ for a suspension of non-interacting hard spheres, while it is lower than this for a gel containing attractive spheres. The spheres shown are representative of a variety of potential thickeners in food systems, including hard and soft particles, microgels, oil droplets, air bubbles, polysaccharides, proteins, plant cells, ice crystals, fat crystals, surfactant vesicles and micelles. (See Stokes and Frith, 2008, for more details.)

starch granules, protein micelles, emulsion drops and air bubbles), surface coatings (e.g. polymer-coated colloids and colloids with long range surface forces), or because of aggregation as elastic clusters and flocs (Dahbi *et al.*, 2010; Stradner *et al.*, 2004; Purnomo *et al.*, 2008; Mezzenga *et al.*, 2005; Meeker *et al.*, 2004). Despite the different nature of a gel and soft-glass microstructure, both are considered to be in an out-of-equilibrium state arising from structural units being in a jammed configuration.

The rheological properties of soft foods are not only set by the interactions between components and the microstructural arrangement, but also by the mechanical properties and shape of the structural components themselves. In a soft glass of microgel particles, for example, the local particle modulus determines the macroscopic rheological properties since in close proximity these can deform and absorb stress in the system (Adams *et al.*, 2004). For foams and emulsions, the strength of the air–liquid and oil–water interface is typically a determining factor.

The generalisation of soft foods as being in a gel or soft glass state allows a necessary simplification of the structure of foods so that the key components that contribute to the rheology of the material can be more easily identified and potentially modelled, including developing an understanding on the influence of environmental changes, shear and time.

11.3.2 Rheology

Soft foods are notoriously difficult to measure reliably under shear using the standard rheological methods described in Section 11.2.4. This difficulty arises from several sources (Stokes and Telford, 2004):

- (1) Deformation in soft materials is not uniform. Samples can flow only in a localised area separated by regions of unsheared sample, and slip can occur in a low-viscosity layer along smooth shearing surface due to depletion of the sample.
- (2) The microstructure is sensitive to shear, which leads to extensive and complex shear history effects. This causes the structure to be modified upon loading into a rheometer.
- (3) The food materials can contain large dispersed phases that bridge the gap in standard geometries.

Such problems lead to substantial errors in rheological measurements, and subsequently lead to misinterpretation of results. For example, in one experience two factory mayonnaise samples were shown on a cone-and-plate to give identical rheological properties, but when dolloped onto a plate even a child could tell from visual inspection that they clearly had different rheological properties (Stokes and Telford, 2004). Standard configurations such as cone-and-plate are not normally suitable for soft foods. The vane tool overcomes most of these problems. It consists of four or more blades that form a cross-shape at the end of a central shaft, so that it can be inserted directly into the sample without overly disturbing the microstructure and thus changing the material's rheological properties upon loading. The fluid circumscribed by the vane moves as a solid cylindrical body such that slip is effectively eliminated. The vane can also be used in situations where a large gap is needed between the blade tips and the outer wall, which eliminates artefacts resulting from the presence of large particulates. The vane can also be inserted directly into actual product containers or jar so that measurements can be performed with virtually no disturbance of the material microstructure that would otherwise occur if loading into a standard cylindrical cup (Stokes and Telford, 2004). A mesh cylinder can also be inserted into sample cups or large diameter tubs to obtain a well-defined outer radius.

Soft foods are highly sensitive to external forces such that they will yield and flow (or fracture) once a sufficient applied stress or strain is obtained. This is observed in Figure 11.7 as a steep decrease in viscosity at a critical stress value measured with a vane, whereupon the constituents rearrange, rotate and/or deform to a state where flow occurs. This is also observed if a constant shear rate is applied to the sample (see insert in Figure 11.7). In this mode, the structure responds to the deformation in an initially linear elastic manner, but as the stress builds, plastic deformation occurs until there is a peak in shear stress at a critical strain. However, while both the critical stress in shear-stress sweep and peak stress measured at a constant shear rate are both termed a 'yield stress', and both can be the same for a particular test sample, both are usually dependent on the exact measurement conditions in a rheometer. For example, longer measurement times during a shear-stress sweep leads to lower values of the critical stress for shear-thinning, while increasing the shear rate during step-shear tests leads to a decrease in the peak stress. This problem is difficult to resolve, and serves to highlight the out-of-equilibrium nature of microstructure. When comparing samples, it is best simply to use consistent conditions for measurement. While a traditionalist seeks to measure a steady state property, such a condition may not be

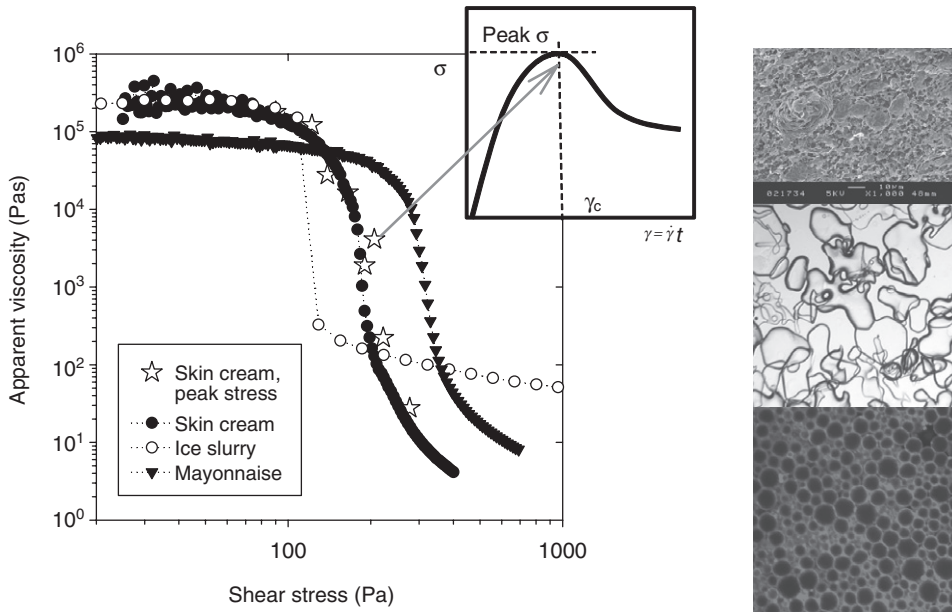


Figure 11.7 Comparison of the apparent viscosity–shear stress relationship of soft materials including skin cream, ice slurry, and mayonnaise. These were obtained using the vane tool as described in (Stokes and Telford, 2004), using short measurement times of typically 5 seconds per point. Also shown are results obtained for the skin cream sample for apparent viscosity values at the peak stress when experiments are conducted at a constant shear rate; the insert is a cartoon of this response. The corresponding microstructures of the material are also shown (from top to bottom: skin cream, ice slurry and mayonnaise).

possible to attain for many soft foods when the structure is also dependent on the strain imposed on it during application of a constant stress or rate over time. Short duration times during shear-stress sweeps (e.g. 5 to 10 seconds per measurement point) match the peak stress in step-shear tests, which may be a good starting point when measuring the rheology of such systems (Stokes and Telford, 2004).

SAOS is the principal technique used to determine the linear viscoelasticity of soft-solid foods. Soft foods are inherently solid-like materials so that $G' > G''$, with both G' and G'' being independent of frequency over the typical measurement range. SAOS can also be used to probe the kinetics of gelation or melting in response to changes in temperature, salt, pH, etc. of soft foods (Stokes and Frith, 2008; Fischer and Windhab, 2011).

Biopolymers are used as one of the principal structuring agents for soft foods (Lapasin and Pricl, 1995). Gel networks can be formed via either covalent bonds or physical associations between polymer molecules. Polysaccharide gelation typically involves non-covalent cross-links forming between biopolymer molecules due to a combination of hydrophobic, electrostatic and/or hydrogen bonding interactions (Ross-Murphy, 1995). Protein gelation typically arises from aggregation of colloidal proteins in much the same way as attractive colloidal spheres (van Riemsdijk *et al.*, 2010), although gelatine is an exception to this behaviour as it gels in a similar manner to polysaccharides. An analysis of the extensive

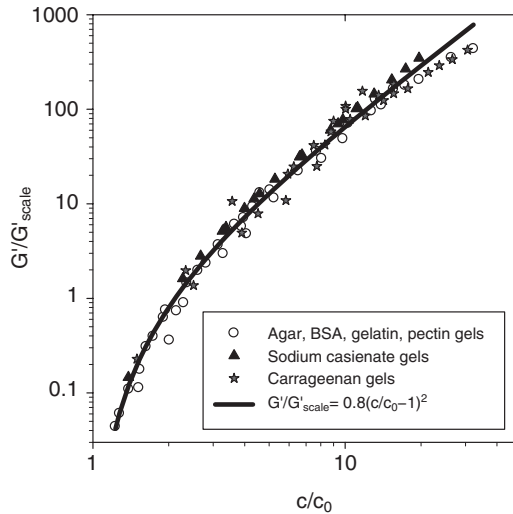


Figure 11.8 Universal response for the scaled storage modulus for a range of differently structured biopolymer gels and a fit to $[c/c_0 - 1]^2$. Data obtained from Clark *et al.*, 2001; Clark and Farrer, 1995; Ruis *et al.*, 2007; Hilliou and Goncalves, 2007).

literature on biopolymer gels reveals similarity for the dependence of modulus on biopolymer concentration, as shown in Figure 11.8. The scaled storage modulus for several different gels, including those made from polysaccharides (agar, pectin and carrageenan) and proteins (gelatin, bovine serum albumin and sodium caseinate) are found to have the same dependency on concentration as follows (Clark *et al.*, 2001; Clark and Farrer, 1995; Ruis *et al.*, 2007; Hilliou and Goncalves, 2007):

$$\frac{G'}{G'_{scale}} \sim \left(\frac{c}{c_0} - 1 \right)^2 \quad (11.12)$$

c_0 is the minimum polymer concentration required for gelation and G'_{scale} is scaling modulus. At high concentrations, 'quadratic' behaviour is typically observed when G' is plotted directly against c (Ross-Murphy, 2005; Clark *et al.*, 2001).

Soft glass microstructure in food materials arises when particles are dynamically arrested (jammed) in a disordered state. This occurs for hard spheres near their maximum volume fraction of ~ 0.6 , at which point the dispersion has an infinite viscosity and solid-like mechanical properties. In stark contrast, soft spheres continue to jam together in a disordered state over far greater concentration ranges by adjusting their shape and volume to accommodate neighbouring particles. Soft glasses also exhibit much softer solid-like mechanical properties that can withstand finite shear stresses before yielding and flowing in a liquid-like manner. The rheology of soft glasses depends on many factors, such as interparticle forces and matrix fluid properties, but a key attribute is the elasticity of individual particles.

Biopolymer microgels, which are spherical hydrogel particles, provide a good model for other soft particulate systems including plant cells and gelatinised starch since the influence of particle modulus and concentration can be easily varied (Stokes, 2011). In concentrated

suspensions, the particles deform in close proximity and/or deswell so that their shear rheology and linear viscoelastic properties depend strongly on particle modulus (Stokes, 2011; Adams *et al.*, 2004). A power-law relationship between the suspension modulus and phase volume of particles occurs, $G' \propto \phi^m$, where $m = 2$ to $m = 8$ being observed experimentally for various microgel suspensions (Senff and Richtering, 1999; Senff *et al.*, 1999; Senff and Richtering, 2000; Adams *et al.*, 2004; Evans and Lips, 1992; Evans and Lips, 1990; Paulin *et al.*, 1996). However, an exact relationship between particle properties (e.g. particle modulus) and suspension rheology has proved difficult to establish even in model systems because of a lack of ability to measure the particle modulus and size under conditions in which it resides in dense suspensions. Evan and Lips (Evans and Lips, 1990) considered the strong repulsive interaction from particle deformation when particles are in close proximity and incorporated the Hertz model for contacting elastic spheres into a pair potential relationship; this approach captured some important features of structure-modulus relationship near the liquid–solid transition point for a range of biopolymer microgels, including gelatinised starch and agar (Adams *et al.*, 2004; Stokes, 2011). However, Adams *et al.* (2004) required an empirical approach to relate suspension properties (G' , σ_y , η) to particle modulus and effective phase volume. Microgels can also be varied in shape in order to understand the influence of particle anisotropy on the rheology of soft materials (Altmann *et al.*, 2004; Stokes and Frith, 2008; Stokes, 2011).

11.3.3 Mechanical properties and fracturing behaviour

For foods that fracture rather than flow following yielding, it is preferable to utilise techniques that are widely used to study the mechanics of hard materials. This includes applying compression or tension to a sample, typically when it is formed into a well-defined cylinder or t-bar shape respectively, or using a three-point bending test on flat sheets or bars (Normand *et al.*, 2001; Michon *et al.*, 2004). The relevant linear mechanical properties include the shear modulus (G) and Young's (tension or compression) modulus (E); these are defined in regions where the material deforms elastically (i.e. its initial state is recoverable when the deformation is removed) (Ferry, 1980). Upon non-linear deformation, important properties include the yield stress for when plastic deformation begins and the fracture stress, as well as the strain corresponding to these two conditions. Following yielding and prior to fracture, solid materials can also undergo strain hardening or strain weakening depending on the material's microstructure and type of deformation.

The fracture properties of biopolymer (polysaccharide and/or proteins) gels have been suggested as a good model for other soft foods that fracture rather than flow beyond a yield stress. As reviewed by Foegeding (2007), in a series of model experiments, model agar and agarose gels have been used to consider the influence of increasing fracture stress while independently varying the fracture strain, that is for the same fracture stress, gel samples were engineered to have different fracture strains. Sensory tests included squeezing samples between the thumb and forefinger, where it was found that the initial force to apply a small deformation and that to fracture a sample correlated significantly to the measured fracture modulus (fracture stress/ fracture strain), while deformability prior to fracture correlated to the measured fracture strain. In contrast, shear modulus (G') did not correlate to either sensory attribute. A similar relationship is observed for mastication in the mouth, although it was additionally found that particle breakdown and chewiness correlated with fracture stress and modulus, while deformability correlated more strongly with the degree of strain

hardening than fracture strain. Whey protein gels have been used to explore the influence of large scale microstructural changes on fracture properties and sensory perception (Foegeding, 2007). These can be made to vary from fine stranded gels to highly particulate whey protein gels; the major differences are that the fine stranded gels hold water during deformation while the particulate gels exude water.

11.4 SOLID FOOD BREAKDOWN AND RHEOLOGY

The mastication process of solid foods is linked to the mechanical properties of the material (hard and soft) as well as the foods' inherent microstructure. Solid food is normally comminuted during the chewing process to form a bolus, and this process is dependent on the size, shape and mechanical properties of the item being consumed (Chen and Lolivret, 2011). The type of material strongly affects the average duration of mastication; for example, Hiiemae and Palmer (1999) reported an average mastication and swallow time of 22 seconds for hard solids such as peanuts and biscuits, and 9 seconds for soft solids such as bananas and spreads, while low viscosity liquids reside in the mouth for around a second (Cichero and Halley, 2006). One concept to have arisen which seems useful for hard, brittle foods is that of 'breakage function' (Lucas *et al.*, 2002). This parameter is the distribution of fragments of broken particles formed per chew, and relationships have been found between it and the food particles toughness and Young's modulus. These correlations depend on the shape of the food; for food in flat sheets, toughness was the defining parameter, while the criterion for thick blocks was square root of the toughness divided by Young's modulus. The breakage function and solid foods generally are discussed in more detail in Chapter 5.

A combination of mastication and saliva also causes aggregation of hard particles derived from brittle foods during mastication. It is the cohesiveness of the resulting bolus that is thought to initiate swallowing rather than just the size of the particles of food (Cichero and Halley, 2006; Agrawal *et al.*, 1998; Prinz and Lucas, 1997). Cohesion arises from broken down food particles being positioned by the tongue so that they pack together and subsequently bind to form a coherent mass as they mix with saliva (Lucas *et al.*, 2002; Prinz and Lucas, 1995). Saliva can also be absorbed into certain particulates to cause their softening, while enzymes within the saliva can assist in chemically breaking down the bolus to initiate the digestion process. Saliva also provides a lubricating coating around the food bolus, which is particularly important when hard materials, which have the potential to irritate oral surfaces and create severe difficulties during swallowing, are broken down. Adhesion of food materials to the oral lining can also be important during oral processing. It can lead to deposits in the oral cavity that can create oral health issues, while during consumption of foods it can lead to negative mouthfeel attributes such as stickiness and tooth-packing (i.e. food stuck in your teeth).

The rheology of the bolus evolves during the mastication process, but it is not often studied in food design. Understanding its rheological properties may be useful in food design, as indicated in a recent study on low-fat cheeses where it was shown that a harder bolus resulted from cheeses with a low lipid-to-protein ratio compared to those with a high ratio (Rogers *et al.*, 2010). Low fat cheese generally has a firmer texture that does not break down during mastication in comparison to full fat cheeses. This study led to the conclusion that the fat phase disrupted the protein network during the chewing process. Hence, while it may be possible to design more nutritional solid foods with similar mechanical properties

to their less nutritious counterparts (e.g. lowering fat, sugar and/or salt), the rheology of the resulting bolus and how the solid material breaks down may be vastly different in the oral cavity, which ultimately dictates how it is perceived.

11.5 SALIVA AND RHEOLOGY

The stimulation of saliva and its interaction with food and beverages makes it a key component in oral processing. However, while its importance is widely acknowledged, understanding or evaluating its impact on oral processing and sensory perception is still lacking.

11.5.1 Saliva

Saliva serves numerous and multiple functions in the oral cavity including: cleansing, solubilisation of food, bolus formation, facilitating mastication and swallowing, food and bacterial clearance, dilution, digestion of starch and lipids, mineralisation and lubrication of oral mucosa (Stokes and Davies, 2007). The secretion of saliva into the oral cavity occurs during the consumption of foods and beverages due to the initiation of both mechanical and chemical stimuli via neural reflexes. Saliva is therefore a critical component during the consumption of food and beverages, and its properties are important to texture, mouthfeel and taste perception, as well as for oral health. For example, the digestion of starch by enzymes in saliva can decrease the thickness perception of foods (Janssen *et al.*, 2007; Janssen *et al.*, 2009), while the disruption of salivary proteins from oral surfaces can result in the sensation of astringency associated with a loss of lubrication (Rossetti *et al.*, 2009). Saliva plays a vital role in the breakdown and perceived texture of food as well as taste perception (Christensen *et al.*, 1981; Guinard *et al.*, 1997; Ship, 1999), and several studies have recently associated the responsiveness and interaction of saliva with particular food components to the food's textural and mouthfeel attributes (Vingerhoeds *et al.*, 2005; Dresselhuys *et al.*, 2008; Benjamins *et al.*, 2009; Silletti *et al.*, 2008; Rossetti *et al.*, 2008). Saliva is also essential for transporting taste molecules to taste receptors, which is evident in patients with xerostomia (dry mouth syndrome) who have been found to have a diminished sense of taste (Christensen *et al.*, 1981; Ship, 1999). More detailed discussion on the properties and functionalities of saliva are given in Chapter 3.

The presence of food and beverages stimulates saliva production. However, the saliva naturally present in the mouth (i.e. resting saliva) and that which is stimulated can be highly variable in terms of composition, abundance and rheology, which make it difficult to study and incorporate into standard testing procedures. It has been found that these properties of saliva are influenced by factors such as stress, hormones, caffeine intake, medical intervention, hunger and even depression (see Stokes and Davies (2007)). When using real saliva for studies on the interaction with food, care is needed to unify collection procedures to ensure sample consistency; for example, saliva should only be collected 1.5–2 hours after eating and it is good practice to avoid donors who are on medication. The flow rate of resting saliva is usually slow, so it is often preferred to stimulate saliva using acid or mechanical action. However, the physical properties of saliva and its composition depend on which method is used. In addition, saliva's physical properties undergo rapid changes *ex-vivo*; it needs to be used immediately after it is stimulated to be representative of what's in the mouth. It is common practice to freeze and/or centrifuge samples before use; however, both of these actions alter saliva's rheological properties (Bongaerts *et al.*, 2007).

so it is no longer a good representation of *in vivo* saliva. Hence, extreme care is needed when handling and using saliva for research studies on oral processing.

11.5.2 Real or artificial saliva to study food-saliva interactions?

A common question that arises in oral processing is whether real or artificial saliva should be used to study the influence of saliva on the interaction between saliva and food. The simple answer is that probably both should be used, along with combined food and saliva obtained directly from the mouth following oral processing (i.e. 'spit out' samples). If real saliva is to be used for *in vitro* tests, then to have it most representative of what's in the mouth it is best to follow a few guidelines: first evaluate both mechanically-stimulated saliva (which predominantly stimulates the parotid gland in the cheek) and acid-stimulated saliva in order to test the two extreme types of saliva; second the saliva should be collected into narrow containers with surfaces having low protein binding properties and limited free-air surface to minimise protein adsorption to air and solid surfaces; third it should be used immediately without delay and all tests performed as quickly as possible. Any centrifugation, filtering or storage of saliva alters its nature, so care must be taken when interpreting studies with such samples. The changing nature of saliva is usually easy to observe by stretching a small amount between thumb and forefinger; initially a thread is formed that lasts several seconds, but if tested periodically over time or after centrifugation, its ability to form a long standing thread is severely diminished.

It should be emphasised that there is no fluid that simulates all (or even some) of saliva's unique physical properties or composition. So the term 'artificial saliva' is very misleading, and it is probably best avoided all together. The scientific approach to understanding food-saliva interactions is to study independently specific properties of saliva. For example, the influence of saliva's buffering capacity on a food's material properties can be studied using a simple buffering solution that maintains a neutral pH. The impact of the polymeric components can be studied using dilute solutions of polyelectrolytes such as mucin solutions (however it must be emphasised that the rheology and interfacial properties of mucin solutions do not replicate those of saliva). The influence of enzymes such as amylase on saliva can also be examined independently of other solution variables. Salt concentration can be varied across the typical range observed in saliva. While such studies are time consuming, it is a way to isolate the different factors that may play a role in the changing properties of food during oral processing. It is also useful to compare model experiments to real saliva.

Another factor worth considering is the mixing process itself. The rate of change in food material properties during the addition of 'saliva' is likely to be important to the dynamics of the food-saliva mixture during oral processing. This was most recently demonstrated for starch suspensions in comparison to a polysaccharide solution (Ferry *et al.*, 2006). The suspensions mixed more efficiently with dyed water (simulating saliva) than the hydrocolloid solution, and it was hypothesised that this greater efficiency was responsible for the increased perception of flavour and saltiness when the viscosity at 50 s^{-1} was matched. In addition, shear during the oral mixing process can breakup and emulsify neat oil in saliva *in vivo* (Adams *et al.*, 2007), while surfactant-coated oil droplets aggregate or coalesce depending on the nature and charge of the surfactant (van Aken *et al.*, 2011; Silletti *et al.*, 2008); such a process could lead to localised regions of increased viscosity. However, in general, soft foods will typically reduce in viscosity during oral processing due to the action of shearing forces in the mouth and temperature change, but also due to dilution and/or chemical breakdown by saliva.

11.5.3 Saliva rheology

Prior to even contacting food, saliva itself has fascinating and important rheological properties that may also affect mouthfeel and other sensory percepts. Early studies on saliva rheology reported it to have a yield stress and $G' > G''$ which has misled several investigators into thinking it is a gel. However, this response arises from adsorption of proteins from saliva to the air – interface where it forms a network, and hence is an interfacial property rather than a bulk rheological property (Stokes and Davies, 2007; Rossetti *et al.*, 2008). The addition of a low concentration of surfactant or low-viscosity silicon oil to the air interface minimises protein adsorption and allows the rheology to be measured without this surface artefact. Saliva is then found not to have a yield stress or gel-like properties, but is instead a weakly shear-thinning but highly elastic fluid with large values of N_1 measured. Its non-linear and linear viscoelastic properties are characteristic of polymer solutions, but unlike flexible polyelectrolytes or polysaccharides, it shows extremely high elasticity for a very low viscosity fluid (Stokes and Davies, 2007). Its rheology is also highly dependent on the method of stimulation. An acid solution and flavourless chewing gum (i.e. acid- and mechanically-stimulated saliva respectively), produce similar amounts of saliva but, as shown in Figure 11.9, the saliva stimulated by citric acid was extremely elastic whereas saliva stimulated by gum was relatively watery and inelastic, while their viscosity flow curves were almost identical. The high elasticity of saliva is expected to arise from the presence of extremely high molecular weight glycoprotein (mucin) that form super-molecules by aggregating end-to-end (Stokes and Davies, 2007; Bansil and Turner, 2006; Strous and Dekker, 1992). Stokes and Davies (2007) suggest that this arises due to secretion of saliva from the sublingual gland, produced in the glands under the tongue, and the sub-mandibular gland, produced behind the lower lips, since their secretions are rich in high

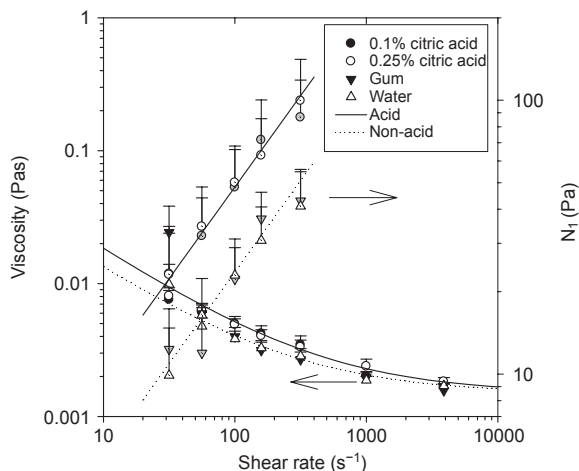


Figure 11.9 The viscosity and primary normal stress differences (N_1 , dotted symbols) of human whole mouth saliva following stimulation using citric acid, chewing gum and water. Significant differences are observed in N_1 between acid and non-acid stimulus, while the viscosity could not be differentiated. Note that the flow rate following chewing gum was similar to that following acid stimulation, but significantly greater than from water. Reproduced from Davies *et al.*, 2009, pp. 2261–2269, with permission from Elsevier.

molecular weight proteins (van Derreijden *et al.*, 1993a; van Derreijden *et al.*, 1993b). In contrast, mechanical action is expected to stimulate primarily the parotid glands, situated near the cheekbones towards the back of the mouth, which gives a relatively inelastic saliva of lower protein content (Stokes and Davies, 2007).

The major finding from Stokes and Davies (2007) is that the physical properties of whole mouth saliva are influenced by the method and type of stimulus, which had not been considered previously in studies aimed at generating an understanding of the role of saliva during oral processing and for oral health. Significant differences are also found in the flow rate and elasticity of saliva stimulated by different beverages, chewing gum and mint (Davies *et al.*, 2009). However, there are no significant differences in the viscosity of saliva stimulated by these stimuli. While the variability between individually donated saliva samples is large, consistent trends are observed whereby acidic beverages such as ice tea and fizzy cola stimulate significantly higher flow rates of whole mouth saliva that is significantly more elastic in comparison to the response from water. This is likely to be a defence mechanism to protect the teeth from acid erosion. However, mechanical action and mint flavour is found to stimulate significantly higher flow rates of saliva compared to that provoked from water, but the saliva has a low elasticity. Hence, saliva elasticity is independent of flow rate. A sensory study showed that this response of saliva to different stimulations may influence a variety of sensory attributes post-consumption, including tongue dryness, mouth moistness, amount of saliva and tongue sensation (Davies *et al.*, 2009). However, a more in-depth study is required involving a greater number of volunteers to determine whether differences in saliva rheology and flow rate can be related directly to the mouthfeel of particular beverages.

11.6 SENSORY PERCEPTION AND THE FLUID DYNAMICS BETWEEN TONGUE AND PALATE

To appreciate how the rheology of food and beverages is important in oral processing, it is useful to consider the basic deformation processes that are occurring in the mouth during consumption. An improved knowledge on oral fluid mechanics would contribute to an improved ability to predict deposition and mass transfer processes (e.g. for taste and aroma perception), bolus formation, as well as resistance to flow that is related to textural properties. A cartoon of the interaction between the tongue and palate is shown in Figure 11.10, along with some of the basic deformation processes taking place.

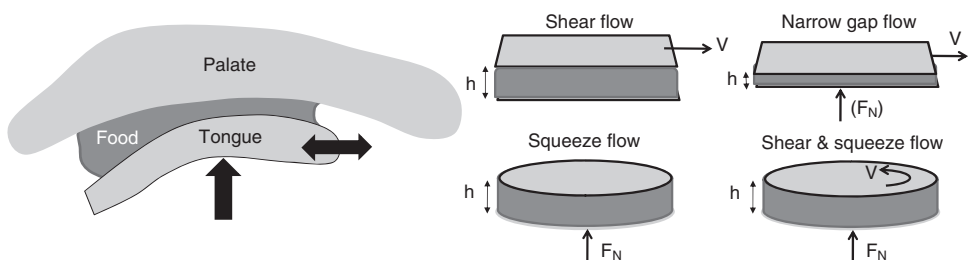


Figure 11.10 Cartoon of the interactions between tongue and palate. The right hand side shows idealised depictions of the fluid dynamics taking place as the tongue moves.

11.6.1 Shear flow

The simplest model describing fluid dynamics occurring in the oral cavity with respect to deformation of food between the tongue and palate is simple shear flow, as depicted in Figure 11.10. The tongue and palate are assumed to be non-deformable flat plates separated by a thin fluid film (as in a rheometer) such that the stress at the tongue surface (σ_T) is simply given by:

$$\sigma_T = f(\dot{\gamma}) \quad (11.12)$$

The shear rate ($\dot{\gamma}$) is equivalent to the velocity of the tongue (V) divided by the distance between the tongue and palate (h), that is $\dot{\gamma} = V/h$, following Figure 11.1a. To determine the response, a velocity and gap or shear rate must be *assumed* and the stress evaluated according to the measured rheological properties. $f(\dot{\gamma})$ represents the constitutive model chosen to represent the fluid, such as Newton's law of viscosity. This simplified model of the tongue–palate interaction can be further expanded to include increased complexity associated with the evolution of fluid properties due to time (t) at a constant shear and thermal changes (TH), which is particularly important in-mouth: $\sigma_T = f(\dot{\gamma}, t)$ and $\sigma_T = f(\dot{\gamma}, t, TH)$. Time dependency includes thixotropy, where the rheology of the material is altered upon shearing over time. Complete constitutive models also require inclusion of terms associated with fluid memory (Barnes *et al.*, 1989), which arise from a material's elastic properties and lead to normal stress differences and extensibility. However, much research is still required to develop viable continuum models that are capable of describing food materials accurately in even simple flows. We restrict our scope here to only the simplest of non-Newtonian properties: shear-thinning.

Most foods are shear-thinning fluids, and when measured over a sufficient range of shear rates they are normally characterised by low-shear plateau in viscosity (termed the zero-shear viscosity, η_0) and a high-shear plateau in viscosity (termed infinite shear viscosity, η_∞), separated by a power-law region as shown in Figure 11.11. However, it is common to only measure the power-law region of the flow curve for fluid foods, which is given by:

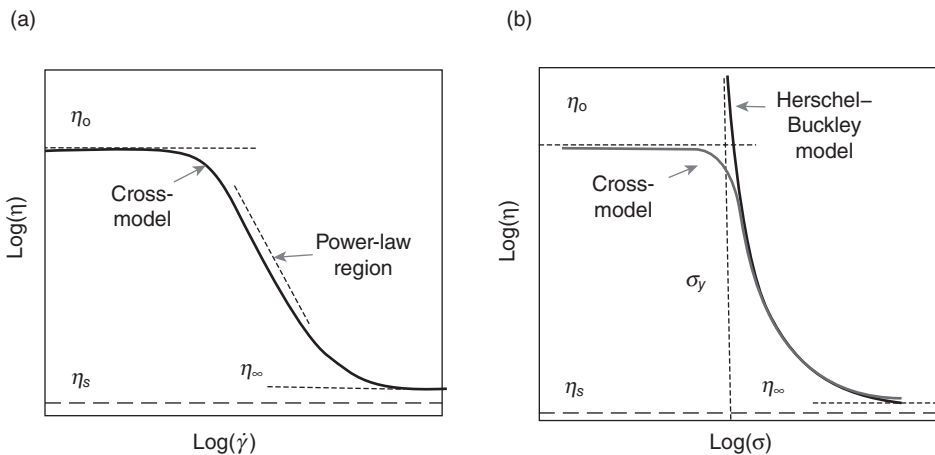


Figure 11.11 Shear-thinning flow curves for (a) liquid foods, normally plotted as viscosity against shear rate on a log scale, (b) soft foods, normally plotted as viscosity against shear stress on a log scale.

$$\sigma = K\dot{\gamma}^n \quad (11.13)$$

On a double logarithmic plot, the flow curve of a power-law fluid will be linear with a slope of n (power-law index) and intercept $\text{Log}(K)$. K (Pa s^n) is the consistency coefficient that is equivalent to the shear stress when $\dot{\gamma} = 1 \text{ s}^{-1}$. The apparent viscosity is given by:

$$\eta = \frac{\sigma}{\dot{\gamma}} = K\dot{\gamma}^{n-1}. \text{ The power-law model reduces to the Newtonian model when } n = 1.$$

Soft foods are more sensitive to shear stress than shear rate, so it is preferable to plot their viscosity profile as a function of shear stress, as in Figure 11.7(b). The Herschel–Bulkley model is an extension of the power-law model and is often used to describe soft foods since they display an apparent yield stress (σ_y), that is a minimum stress must be exceeded to cause flow:

$$\sigma = \sigma_y + K\dot{\gamma}^n \quad (11.14)$$

However, the observation of a ‘true’ yield stress as described by the Herschel–Bulkley model is dependent on the measurement procedures and equipment (Stokes and Telford, 2004).

Two further empirical models that are successfully used in the study of both fluid foods and soft foods because they capture the zero-shear plateau in viscosity, power-law region and an infinite-shear plateau viscosity are the Carreau and modified-Cross models respectively:

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + (\lambda_c \dot{\gamma})^m} \quad (11.15)$$

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + \left(\frac{\sigma}{\sigma_c}\right)^m} \quad (11.16)$$

λ_c is a time constant that has been related to the relaxation time of polymers in solution. σ_c is a critical stress at which the fluid becomes shear-thinning; many so-called yield stress fluids and soft foods follow these models, so that $\sigma_c \sim \sigma_y$.

11.6.2 Shear flow and sensory thickness: what is the shear rate in the mouth?

The simple approach of considering the tongue–palate as two flat plates has been used as a basis for attempting to associate food materials’ sensory properties to a single shear rate in the mouth. It is now almost commonly, and conveniently, ‘accepted’ that the shear rate in the mouth is 50 s^{-1} . However, this is a very misleading assumption since this shear rate has only been substantiated for oral thickness perception of mainly fluid foods. In addition, it should always be recognised that food is exposed to a range of shear and deformation processes during oral processing, and hence it is anticipated that the governing material response determining flow behaviour and affecting sensory perceptions will vary during the consumption process.

The origin of the finding that 50 s^{-1} is representative of the shear rate in the mouth arose from the study of Wood (1968) who correlated the perceived thickness of fluid foods with their rheological properties (Stanley and Taylor, 1993). By thickening soups using a variety of hydrocolloids, Wood (1968) compared thickness perception with that of Newtonian fluids to find that these corresponded to the shear stress (or viscosity) at an approximately constant shear rate of 50 s^{-1} . However, only a limited number of relatively similar non-Newtonian fluids were used. Sharma and Sherman (1973a, 1973b) evaluated a greater number of fluids and semi-fluids, but used paired comparison tests to differentiate numerous groups of samples that had similar flow characteristics. On the basis of panellists' responses and the rheological data, they estimated shear stress–shear rate bounds operative in the evaluation. While their results agreed with those of Wood (1968) for the limited ranges of viscosities he studied, they concluded that shear rates ranging from $\sim 10\text{ s}^{-1}$ to over 1000 s^{-1} are present when orally evaluating thickness that depended on the sample's rheology. They hypothesised that the most fluid samples ($< 70\text{ mPas}$) are defined orally by the shear rate developed at an approximately constant shear stress of 10 Pa , but more viscous samples involve the shear stress developed at a low shear rate of approximately 10 s^{-1} . Cutler *et al.* (1983), however, found no evidence for the inflexion point observed by Sharma and Sherman (1973a) when studying the thickness perception of Newtonian fluid foods. In addition, Christensen (1979) studied the thickness perception and rheology of highly shear-thinning and viscous hydrocolloid solutions and also did not find evidence to support Sharma and Sherman's hypothesis. Morris *et al.* (1982, 1984) studied an extensive range of fluid foods that included weak gels. They found that the Sharma and Sherman method was suitable for many of the fluid samples studied, but increasingly failed as the shear-thinning nature of the fluid was increased. For highly shear-thinning fluids that were classed as weak gels, the perceived thickness was also underestimated by an order of magnitude when compared to Woods's shear rate of 50 s^{-1} , although the correlation was improved when comparisons were made at 10 s^{-1} (Cutler *et al.*, 1983; Morris *et al.*, 1984; Morris and Taylor, 1982). Improved correlations were also found by using the complex viscosity obtained from linear viscoelastic measurements at a frequency of 50 rad/s (Richardson *et al.*, 1989). It is unclear why this would be the case. While for true solutions and many fluids the complex viscosity is very similar to the shear viscosity as functions of frequency and shear rate respectively, this is not the case for highly structured fluids and soft foods. Richardson *et al.* (1989) acknowledge that this is a surprising result, as it is unclear why small deformation measurements should translate to a sensory response during a process that is likely to involve large strains. They hypothesise that the dynamic measurements reflect the state of the unperturbed network structure of weak gels that may also be related to the peak shear stress that is required to rupture the network when a constant shear rate is applied to the weak gel. However, no evidence was provided to support this idea and previous experiments by Dickie and Kokini (1982, 1983) that related the peak stress to sensory thickness of structured fluids had poor correlation coefficients (this is discussed further in Section 11.6.4). Dea *et al.* (1989) also found correlations using complex viscosity measurements at 50 rad/s , and showed that these correlated closely with the activity of the muscles that control tongue movement as measured by electromyography.

At this stage, a universal 'shear rate' that can be used for thickness perception of non-Newtonian foods does not exist. However, it seems reasonable that for *liquid* foods the viscosity at shear rates of around 50 s^{-1} or 50 rad/s is a *reasonable* predictor; by liquid food we mean systems where the viscosity is less than 100 mPas and that they are not soft foods that include weak gels and highly shear-thinning fluids. Weak gels are those fluids where

the storage modulus is greater than the loss modulus, and the viscosity drops dramatically by several orders of magnitude at a specific shear stress (i.e. it possesses an apparent yield stress). However, caution should always be exercised when using a single shear rate measurement for evaluation on non-Newtonian fluids! Different fluids may vary dramatically above and below the chosen shear rate, which may have important consequences during oral processing beyond 'thickness' perception. The complex viscosity at 50 rad/s (at a strain or stress that lies within the linear viscoelastic regime of the sample) may also be a relevant measure of oral thickness for a greater range of sample rheologies. However, it is still an open question why it should correlate, and again caution should be exercised in assuming it is a universal relationship until such time as the mechanism is clear.

In a wider oral processing context, it must be emphasised that the aforementioned studies are in fact only investigating thickness perception. While a particular shear rate or frequency may correlate with thickness perception, it does not mean that this value is the shear rate or frequency in mouth. Other attributes may well correlate with other shear rates, shear stresses or other rheological variables other than viscosity. For example, food is sheared between tongue–palate where these surfaces are only prevented from touching by a finite layer of the food (and saliva) sample; under this condition the calculated shear rate is greater than 1000 s^{-1} which is more than most rheological studies in food research. While this shear rate is perhaps not relevant to initial thickness perception, it may well be the determining factor for other late time attributes (including 'mouthfeel') and tastants that depend on mass transfer to the receptors.

As reviewed by Hiimeae and Palmer (2003), a detailed study on tongue movement during oral processing of liquids showed that the average tongue speed was 10.34 mm/s, SD 2.1 (Peng *et al.*, 2000). Thus, to obtain a shear rate of 50 s^{-1} , a film thickness of $200\text{ }\mu\text{m}$ is required for a plate moving at 10 mm/s. However, maximum speeds of 300 mm/s (Peng *et al.*, 2000) and 200 mm/s (Tasko *et al.*, 2002) have been reported during oral processing of liquids, which would mean a gap between tongue–palate of around 5 mm is required to achieve a shear rate of 50 s^{-1} , or if a gap of $200\text{ }\mu\text{m}$ is assumed then the shear rate is around 1000 s^{-1} . In general, all these 'numbers' seem reasonable estimates for the tongue–palate interaction, but it is however extremely difficult to measure the true film thickness. Since the tongue also presses against the palate in the normal direction the film thickness is likely to be changing continuously, which is considered in subsequent sections.

11.6.3 Squeeze flow

The second 'simplest' model to consider for describing oral processing is the squeeze flow between tongue and palate, thus allowing estimates to be made on the evolution of the film thickness upon compression of liquid and soft foods. In this case, the tongue and palate are assumed to be non-deformable substrates and the normal load that the tongue applies is considered constant. However, squeeze flow creates a complex flow field since it involves a combination of shear and extension that depends on the assumptions chosen (or surfaces chosen in the case of experiments). One of the key assumptions in squeeze flow is the boundary condition at the plate surfaces, which range from non-slip to perfectly lubricating. This choice alters the model equations considerably, as reviewed by Engmann (2005), which is the major issue with the use of squeeze flow as a relevant rheological test. Hence, while it is a seemingly simple test that has similarities to processes occurring in the mouth, it is a very difficult measurement to interpret. We briefly highlight some key equations in squeeze flow for Newtonian, power-law and Herchel–Bulkley fluids since these are the

simplest to consider. More detailed analysis is required for more complex fluids and soft solids.

If a *non-slip* boundary condition is assumed at the surface of two circular plates of radius R that are compressed together either at a constant force (F_N) or speed ($\dot{H}$), and any material extruded from the gap does not contribute (i.e. constant sample area), then the normal force on the plates as a function of fluid parameters is given for a Newtonian fluid and power-law fluid by:

$$F_N = -\frac{3\eta\pi R^4 \dot{H}}{2H^3} \quad (11.17)$$

$$F_N = -\frac{2\pi}{n+3} \left(\frac{2n+1}{n} \right)^n \frac{R^{n+3}}{H^{2n+1}} K \dot{H} |\dot{H}|^{n-1} \quad (11.18)$$

Equation 11.17 for the Newtonian fluid is commonly referred to as the Stefan equation. In the case of a Herschel–Bulkley fluid, a solution in the lubrication limit for squeeze flow with a non-slip boundary condition was derived by Adams *et al.* (1994) (see also (Yan *et al.*, 2010, Meeten, 2002; Meeten, 2010)):

$$F_N = -\frac{2\pi R^3 \sigma_y}{3H} + 2\pi \left(\frac{2n+1}{n} \right)^n \frac{R^3}{H} \left(\frac{R\dot{H}}{H^2} \right)^n \quad (11.19)$$

If *perfect slip* is assumed at the contact with the plates, a uniform biaxial extension occurs with a rate of compression given by $\dot{\epsilon} = \frac{\dot{H}}{H}$. For a generalised Newtonian fluid with viscosity function $\eta(\dot{\gamma})$ evaluated with $\dot{\gamma} = \sqrt{3}|\dot{\epsilon}|$ and neglecting inertia, the normal stress on the plate is $\sigma_{zz} = \frac{F_N}{\pi R^2} = 3\eta(\dot{\gamma})\dot{\epsilon}$ (Engmann *et al.*, 2005). Thus for a Newtonian fluid and power-law fluid, their respective normal stresses assuming constant volume are follows:

$$\sigma_{zz} = 3\eta\dot{\epsilon} \quad (11.20)$$

$$\sigma_{zz} = -3^{(n+1)/2} K |\dot{\epsilon}|^n \quad (11.21)$$

If a constant plate speed ($\dot{H}_0 = \dot{\epsilon}_0 H_0$) is assumed, and noting $H = H_0 + \dot{H}t$, the compression rate is then given by $\dot{\epsilon} = (H - H_0)/Ht$. The gap can then be expressed as a function of the experimental parameters as a function of time, which for a Newtonian fluid is: $H = H_0 e^{-\sigma_{zz}/3\eta}$. For a Herschel–Bulkley fluid squeezed with perfect slip between two flat circular plates, an equation for the normal stress is (Meeten, 2002):

$$\sigma_{zz} = \sqrt{3}\sigma_y + 3^{(n+1)/2} K \left(\frac{\dot{H}}{H} \right)^n \quad (11.22)$$

The validity of either the non-slip or perfect slip, and their relevance to the flow properties of food in the mouth has not been fully explored, although there are many examples of squeeze flow experiments being used to characterise food materials (Engmann *et al.*, 2005;

Hoffner *et al.*, 1997; Campanella and Peleg, 1987; Meeten, 2002; Mossaz *et al.*, 2010). Suffice to say, either approach may be considered logical and would depend on the particular food being examined. Saliva-coated substrates that are thus lubricating may be considered to suggest that a perfect slip is present, but on the other hand saliva is also used to bind food substances to form the bolus and so only partial slip may be present. Some foods may penetrate the saliva layer and be sheared directly against the tongue–palate or teeth, and hence then the non-slip condition is valid. This realisation of this level of complexity is still largely unexplored in the realm of oral processing.

In general, caution should be exercised when attempting to use squeeze flow to characterise the rheological properties of fluids and soft solids. To obtain meaningful interpretation of the observed measurements of F_N , $\dot{H}$, or $H(t)$, knowledge of an appropriate model is required that isn't necessarily obvious. Squeeze flow is a non-ideal deformation, and for shear rheology it is far easier and more reliable to utilise conventional rotational geometries.

11.6.4 Shear and squeeze flow: defining an oral shear stress?

We consider here the combination of both shear and squeeze flow, since this is more realistic representation for the movement of the tongue against food and the palate. Consideration of this process increases the complexity of the fluid mechanics further, and there are no detailed studies except for the pioneering works of Kokini and Cussler that are described below.

DeMartine and Cussler (1975) combined the two deformation types to obtain an equation for the shear stress in this flow type. They took the simple approach of defining the gap between the plates through the non-slip squeeze flow equations, as detailed above. This prediction for gap was substituted into the equation for simple shear flow, $\dot{\gamma} = V/H$. For Newtonian fluids and power-law fluids, this gives the following equations for the shear stress respectively:

$$\sigma = \eta^{0.5} F_N^{0.5} V \left(\frac{4t}{3\pi R^4} \right)^{0.5} \quad (11.23)$$

$$\sigma = KV^n \left[\frac{1}{H_0^{(n+1)/n}} + \left(\frac{n+1}{2n+1} \right) \left(\frac{(n+3)F_N}{2\pi KR^{n+3}} \right)^{1/n} t \right]^{\frac{n^2}{n+1}} \quad (11.24)$$

Kokini *et al.* (1977, 1987) estimated the velocity of the tongue, normal force and area of the food sample: $V = 2 \text{ cm/s}$, $F_N = 1 \text{ N}$, $R = 2.5 \text{ cm}$, $H_0 = 0.2 \text{ cm}$. A time basis of $t = 1 \text{ s}$ was also assumed for the perception of thickness. This equation was validated for liquid foods and model hydrocolloid solutions, and the predicted stress from Equation 11.23 or 11.24 correlated to the *initial* sensory thickness as 'sensory thickness $\sim \sigma^{0.93}$ '. Cutler *et al.* (1983) utilised this model to evaluate 45 fluid foods and model systems, including chocolate spread, tomato ketchup, syrups, gum and pectin solutions and obtained a slightly different scaling, which was thought to be due to some of the samples exhibiting transient shear stresses. Cutler's data has been replotted in Figure 11.12, and it is shown that the slope on a log–log plot is 1.5 with $r^2 = 0.90$. In addition, the viscosity at 50 s^{-1} was obtained from the parameters provided for the power-law model (Elejalde and Kokini, 1992), and it is found that this also correlates with sensory thickness to the same level of accuracy (log–log slope = 1.1, $r^2 = 0.91$). On analysis of the shear rate corresponding to the Kokini shear

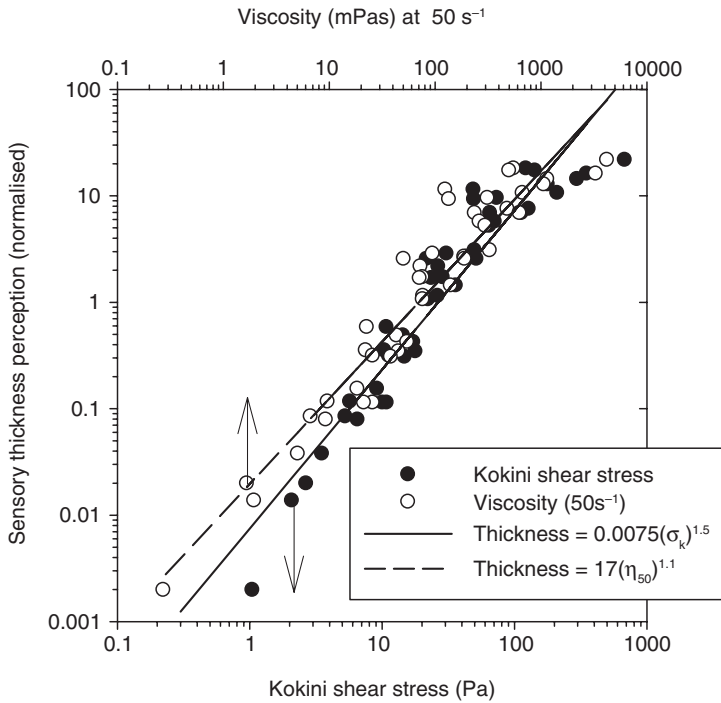


Figure 11.12 Normalised thickness perception of a range of food and model fluids correlated to the Kokini shear stress with $r^2 \sim 0.9$. Data obtained from Elejalde and Kokini, 1992. Also included is a correlation to the viscosity measured at 50 s^{-1} .

stress, it does not vary dramatically across the vast ranges of samples; from 10 s^{-1} for the most viscous samples (chocolate spread), to 415 s^{-1} for the thinnest samples (milk). Therefore, the use of the Kokini shear stress model as stated does not add significant improvement over assessment using a constant shear rate of 50 s^{-1} (see also (Terpstra *et al.*, 2005)). However, varying the parameters in the model, and also incorporating the use of the Herschel–Bulkley model into its formulation for the foods systems with yield stress, has yet to be performed and may provide a means with which to improve accuracy. The Kokini model for a Herschel–Bulkley fluid is:

$$\sigma = \sigma_y + KV^n \left[\frac{1}{H_0^{(n+1)/n}} + \left(\frac{n+1}{2n+1} \right) \left(\frac{(n+3)F_N}{2\pi KR^{n+3}} \right)^{1/n} t \right]^{\frac{n^2}{n+1}} \quad (11.25)$$

Equation 11.25 has been commonly referred to as the Kokini shear stress, and attempts have been made to relate this stress to other sensory attributes such as flavour and taste perception. Using a range of biopolymer solutions, Cook *et al.* (2003) found that increasing the biopolymer concentration beyond C^* suppressed the perception of sweetness and banana flavour. These percepts were found to correlate with the Kokini shear stress through a power-law relationship above C^* , with $r^2 = 0.86$ and $r^2 = 0.94$ respectively, as shown in Figure 11.13. However, using the rheological parameters provided in the original manu-

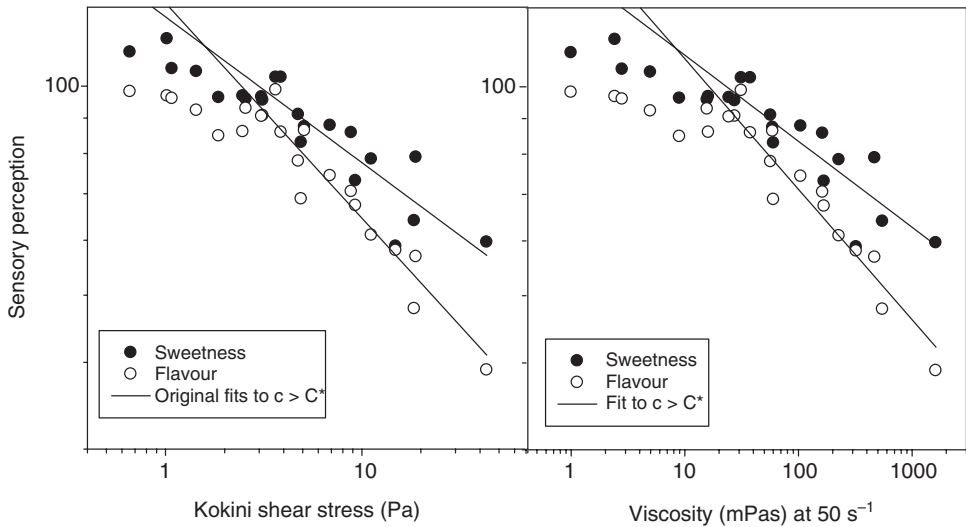


Figure 11.13 Sweetness and banana flavour perception in a variety of polysaccharide solutions correlates above C^* to the Kokini shear stress. Data obtained from Cook *et al.*, 2003. Also included is a fit to the viscosity at 50 s^{-1} .

script, Figure 11.13 shows that the viscosity at 50 s^{-1} also correlates with sweetness and flavour perception with similar accuracy to the Kokini shear stress.

The Kokini shear stress model is perhaps a logical approach to characterising the deformation process occurring in the mouth, although it does not apparently improve correlations to thickness perception. The approach could certainly be extended to consider more complex food models and processes, including temperature changes and variations with time (Kokini, 1987). Dickie and Kokini (1982, 1983) did consider the influence of time of shear for an extensive range of soft and viscous foods using this same approach, but resorted to simply looking at the maximum shear stress with time of shear at a particular shear rate. It was found that this peak stress correlated reasonably well ($r^2 = 0.87$) to thickness perception; it should be noted that for the soft food samples, this peak stress is anticipated to be the same as the yield stress (e.g. see earlier discussion and Stokes and Telford (2004)).

It must be emphasised that while the Kokini approach has led to 'realistic' representation for *initial* thickness perception, it is not 'the shear stress in the mouth' since beyond $t = 1 \text{ s}$ the food material will be exposed to a considerably larger range of increasing shear rates as the film thickness decreases. The material properties of the food bolus may then be drastically different from those measured in the rheometer, in addition to changes induced by mixing/interacting with saliva and from temperature. Another important point is that Equations 11.23–11.25 are not truly solutions to the equations of motion for a combination of squeeze and shear flow, and while the equations have been used to correlate to sensory data, there is no comparison to experimental measures of complex fluids undergoing combined shear and squeeze. The full flow problem has been tackled using the Navier–Stokes equations for Newtonian fluids by Lawrence (1985) and Nicosia and Robbins (Nicosia and Robbins, 2001) for a cylinder of fluid between two rigid plates. This is solved numerically, and for fluid viscosities of order 1 mPas , a maximum shear rate of over 10^6 s^{-1} is predicted to occur. However, no examination of non-Newtonian fluids has been reported, at least not in the context of oral processing.

The combination of shear and squeeze flow is also studied in the tribology literature, and this is reviewed in Chapter 12. A tribological approach allows the oral surfaces to be represented more accurately by using deformable substrates, and thus coupling the elasticity equation for solid deformable surfaces with the equations of motion (de Vicente *et al.*, 2005).

11.6.5 Micro-rheology: gap dependency, confinement and slip

Soft foods are multi-phase fluids, and the dispersed phase may range from colloidal dimensions (< 1 micron) to macroscale particles greater than 100 microns, all of which can range from being hard to soft. All of the previous discussion on rheology and fluid mechanics assumes that the food material (or saliva–food mixture) behaves as a continuum. This is unlikely to be a valid assumption if there is anything other than colloidal entities present in mouth. For example, grittiness is a common mouthfeel perception when hard particulates are present in the food sample, while this is avoided if particles are soft. At moderate phase volumes ($\phi < 40\%$), bulk rheological measurements are essentially indistinguishable between soft and hard particles. However, the perception of grittiness for hard particles implies that during shear, the particles are confined to narrow length scales where their hardness is detectable by human senses. Davies and Stokes (2005, 2008) and Clasen (Baik *et al.*, 2008; Clasen *et al.*, 2010; Clasen and McKinley, 2004) have begun to explore this idea, and probed the influence of microscale confinement on the dynamics of model food systems. It is clear that as you confine suspensions of particles to close to their particle size, the modulus of the suspension increases dramatically, dependent on the particle hardness. This also increases the yield stress of the suspension. Another important feature that is beginning to be explored is wall-slip. The dynamics of soft materials change significantly if any slip is present (Davies and Stokes, 2008). Given that one of saliva's many functions is to lubricate oral surfaces, inducement of slip between materials and the wall is clearly in its job description. Hence oral-slip is an important factor to consider in the oral processing of food systems. More research is needed to understand the relevance and measurement of the gap-dependent rheology and slip of foods, and how it influences both the sensory perception and, more importantly perhaps, swallowing function.

11.7 CONCLUDING REMARKS

This chapter has highlighted some of the important aspects of rheology that are relevant during oral processing of foods and beverages, and it is envisaged that this overview will inspire interested readers to learn further and have a greater appreciation for rheology. There are still many unknowns in the field, and it is ripe for further exploration. Developments are required to consider appropriate and more complex constitutive models for food systems, and to incorporate into a fluid dynamics model the range of deformation processes that are occurring during oral processing as well as accounting for the influence of mixing and interacting with saliva. Significant developments are also required to substantially improve our understanding and measurement of saliva's role during oral processing. In addition, we still have a limited understanding on how rheological properties influence sensory perception. For foods with broad ranging material properties, the viscosity at a single shear rate correlates to some sensory percepts (e.g. thickness), albeit with a relatively poor correlation coefficient of ~ 0.9 – although it is perhaps reasonably accurate given the multi-modal nature

of our sensory processes. However, when foods or liquids are relatively similar, the discriminating power is severely diminished and it becomes more unsatisfactory as a design tool. Further work is thus needed to discover how rheological and/or microstructural properties translate to a sensory percept, which may require new techniques and approaches. This includes more complete rheological characterisation of food materials as well as considering how these properties alter during their interaction with saliva, temperature and time. This need is becoming increasingly more important as manufacturers seek to create next-generation processed foods with significantly improved nutritional benefits, for example by lowering fat, sugar and salt whilst increasing phytonutrients and proteins. However, decreasing in so-called 'bad ingredients' and increasing 'good ingredients' pushes products into uncharted formulation space where the existing design rules no longer apply, and unfortunately it invariably compromises consumer acceptability due to the negative sensory attributes that arise. Further research into understanding oral processing and how it is influenced by food rheology and structural characteristics is certainly required for improving food design.

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12 'Oral' Tribology

Jason R. Stokes

12.1 INTRODUCTION

Tribology concerns the friction, wear and lubrication of interacting surfaces in relative motion; the word tribology is derived from the Greek word 'tribos', meaning rubbing or sliding. Interacting surfaces in relative motion include those that may be rolling or sliding, as well as those in normal approach or separation (Stachowiak and Batchelor, 2005). Such surface interactions dictate or control the functioning of practically every manmade device and are of utmost importance to the engineering of gears, bearings, seals, clutches, couplings, cams and so on. Plants and animals also contain interacting surfaces and biolubricants that have evolved for specific tribological functions that we are still trying to understand; examples include the feet of the gecko (Autumn *et al.*, 2000) that allow it to walk on ceilings and the lubrication between human joints (Mow *et al.*, 1992).

Oral processing also includes 'interacting surfaces in relative motion', whether it is between gnashing teeth, tongue–palate, tongue–teeth, teeth–food, tongue–food, lips, lips–food and so on. Hence, the study of oral processing can easily be considered to be rooted in the science of tribology. While a rheometer characterises materials at a fixed gap, tribology characterises materials at fixed load so that the gap can vary down to where two surfaces are essentially touching. In essence, rheology may be considered more important in the initial stages of oral processing (large gap) but tribology becomes increasingly important with time as the masticated food is processed and shear surfaces interact; there is a transition from a rheology to a tribology dominated process. At the end stages of oral processing, it is likely to be the subtle changes in tribological properties of the salivary film coating and food residue that determines mouthfeel and afterfeel. However, we are only now beginning to explore 'oral tribology' and to determine how we may utilise it to develop a greater understanding of oral processing of food and beverages. This may lead to greater insight into how particular ingredients in a food matrix influence oral processing and the sensory perception of the food.

An example of the potential for investigating the tribological properties of food is highlighted in Figure 12.1, which compares the shear rheology and lubrication properties of full fat and low fat mayonnaise. The low-shear viscosity, yielding behaviour and storage modulus of the two samples are essentially identical, which demonstrates the skill with which product developers are able to engineer food material properties with fat substitutes.

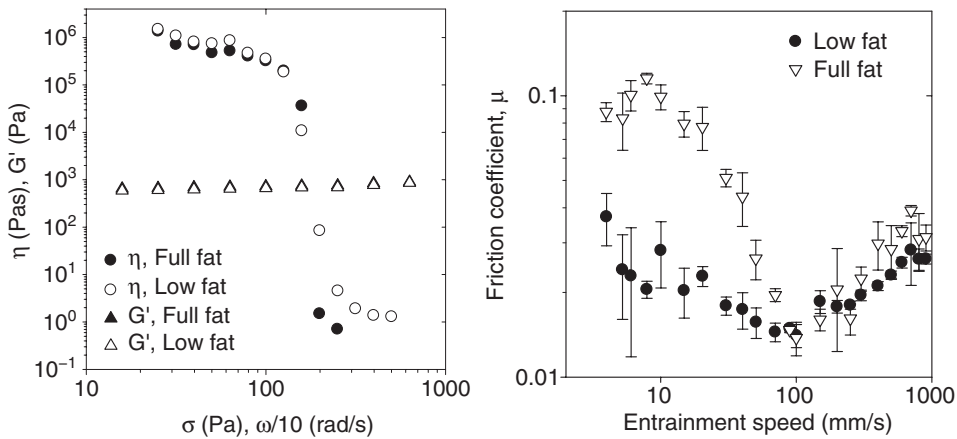


Figure 12.1 Comparison between full fat and low fat commercial mayonnaise samples of the same brand, showing: (a) rheological properties measured using vane-in-jar technique (Stokes and Telford, 2004) show identical modulus and yielding properties; (b) tribological measurements on a mini-traction machine (de Vicente *et al.*, 2006b) measured with a steel ball loaded and rolling/sliding against hydrophobic elastomeric disk (load of 1.3 N) showing distinct differences at low entrainment speeds.

However, standard rheological measurements do not capture the commonly observed differences in the mouthfeel of low fat and high fat foods. When placed in a tribometer comprising a steel ball under load and rolling/sliding against a hydrophobic elastomeric disk, distinct differences in the friction coefficient are observed. These results highlight the fact that the two products are different, despite their matching rheological properties. Understanding the origin and meaning of the difference and how it may relate to sensory properties is still a challenge, but the result clearly highlights the potential of tribology to provide additional information about the dynamics of foods under the tribological conditions present during oral processing.

This chapter provides an overview of ‘oral tribology’, with an introduction to the science of tribology followed by a review of the relevant literature in relation to food lubrication.

12.2 PRINCIPLES OF TRIBOLOGY

The science of tribology principally involves studying the characteristics of the film situated between contacting bodies and the consequences of its failure or absence. There are a number of regimes and mechanisms by which lubrication occurs that principally depend on the film thickness. The following section summarises these key regimes and identifies key properties of the lubricant and surface that influence a system’s tribological response.

12.2.1 Hydrodynamic lubrication and the Reynolds equation

Hydrodynamic lubrication arises from the hydrodynamic pressure of liquid entrained between sliding surfaces (Reynolds, 1886). In general, for hydrodynamic lubrication to prevail the surfaces must move relative to each other with sufficient velocity to generate a load carrying lubricating film and the surfaces must be inclined at some angle to each other,

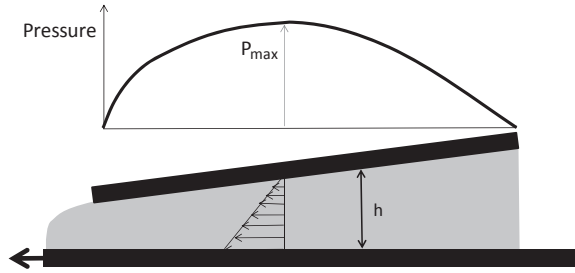


Figure 12.2 Depiction of a non-parallel slider showing the generation of normal pressure that keeps the surface separated.

if the surfaces are parallel a pressure field will not form in the lubricating film to support the required load. For two non-parallel surfaces, the Reynolds equation is derived from the Navier–Stokes (i.e. Newtonian fluids) and continuity equations, which for the assumption of a steady film thickness and constant viscosity (isoviscous assumes thermal influences on the viscosity are neglected) gives:

$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(h^3 \frac{\partial p}{\partial y} \right) = 6U\eta \frac{dh}{dx} \quad (12.1)$$

h is the distance separating the surface, x and y are the distances in the flow and vertical directions respectively, U is the relative speed of the sliding surfaces, and p is the pressure. The pressure along the inclined surface is parabolic and acts to keep the surfaces apart, as depicted in Figure 12.2. This forms the basis for hydrodynamic lubrication.

While the Reynolds equation assumes a steady state situation, this is not the case at startup and shutdown where films are squeezed together. Squeezed films can be considered by including the change in film thickness with time:

$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(h^3 \frac{\partial p}{\partial y} \right) = 6U\eta \frac{dh}{dx} + 12\eta \frac{\partial h}{\partial t} \quad (12.2)$$

These equations serve to highlight the fact that the most important lubricant property controlling hydrodynamic lubrication is viscosity.

12.2.2 Elastohydrodynamic lubrication

Elastohydrodynamic (EHD) lubrication considers the role of elastic deformation of the contacting bodies and the changes in viscosity with pressure in hydrodynamic lubrication. Two contacting surfaces deform under load, either elastically (recoverable deformation) or plastically (non-recoverable deformation). Many engineering contacts involve non-conformal surfaces and small contact areas and thus high pressures that in these contacts. Hertz developed a theory of elasticity that is commonly used in tribology, and this forms the basis for models on elastohydrodynamic lubrication. The surfaces in a Hertzian contact deform elastically, with the principal effect for a ball-disk geometry being a central region of quasi-parallel region between inlet and outlet surfaces as shown in Figure 12.3 (Cassin *et al.*, 2001; Stachowiak and Batchelor, 2005). The film geometry will be dependent on the

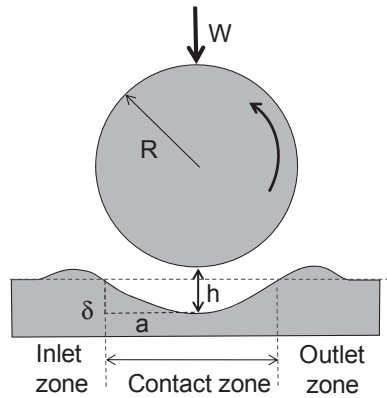


Figure 12.3 Schematic of the deformation of elastic surface from pressure in a ball-on-plate contact. For Hertzian contacts, the contact radius is $a = \sqrt[3]{3WR/4E'}$, depth of indentation is $2\delta = a^2/R$, and maximum contact pressure is $P_0 = \frac{1}{\pi} \sqrt[3]{6WE'^2/R^2}$.

applied load and material properties as well as lubricant viscosity (these are defined using dimensionless parameters as detailed in de Vicente *et al.*, 2005a; Hamrock and Dowson, 1977, 1978; Hamrock *et al.*, 2004), and there are four well-defined lubrication regimes in full-film elastohydrodynamics:

- isoviscous–rigid (i.e. classical hydrodynamics);
- piezoviscous–rigid (high pressure increases film viscosity);
- isoviscous–elastic (elastic deformation of surfaces);
- piezoviscous–elastic (pressure increases viscosity and elastically deforms substrates).

For highly deformable substrates, such as the tongue–palate surfaces, the *isoviscous–elastic regime* is the most relevant such that the pressure in the film deforms the surfaces rather than influences the viscosity of the fluid (Cassin *et al.*, 2001; Hamrock *et al.*, 2004). In practical terms, this type of lubrication occurs either when one of the containing surfaces has low elastic modulus, such as rubber or human tissue, or, for stiffer materials, where the lubricant has a very low pressure–viscosity coefficient and is typically water (de Vicente *et al.*, 2005a).

12.2.3 Film thickness and friction in isoviscous elastohydrodynamic lubrication

In a static contact, classical Hertzian theory predicts a hemispherical or ellipsoidal pressure distribution profile through the contact (Stachowiak and Batchelor, 2005; Hamrock *et al.*, 2004). This pressure distribution will change when surfaces are in relative motion and a hydrodynamic film is being generated. In elastohydrodynamic lubrication, the pressure is lower than the Hertzian value in the entry and exit regions of the contact. The surfaces are almost parallel in the contact zone (see Figure 12.3), which is often described by a central film thickness, h_c . However, there is a peak in pressure just past the central region that is larger than the Hertzian contact pressure, and a constriction is typically found towards the

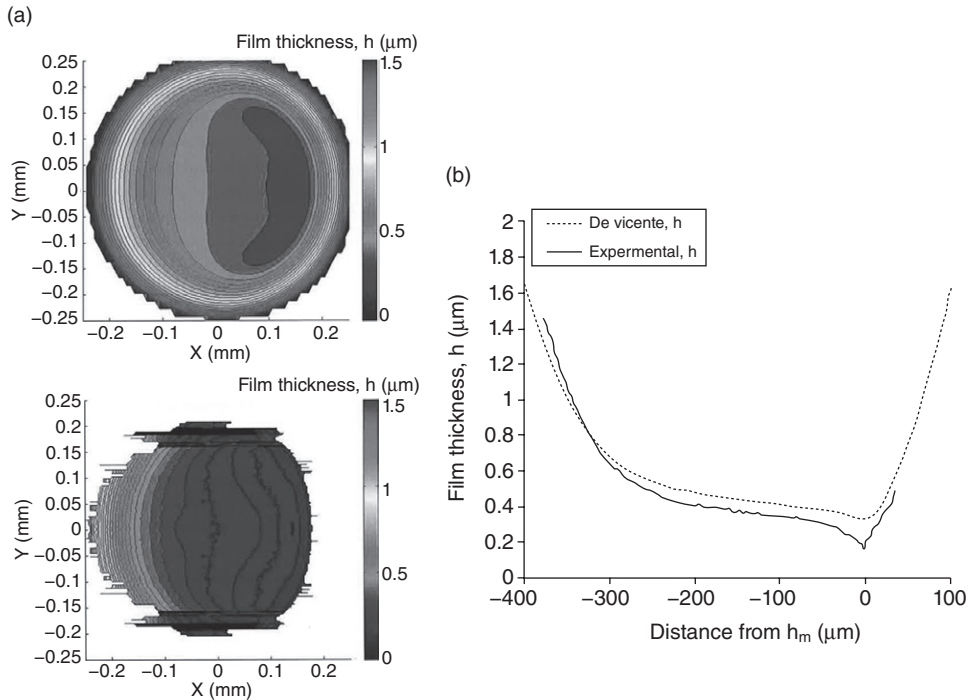


Figure 12.4 Experimental optical interferometry measurements in the elastohydrodynamic regime between a PDMS-coated ball and glass disk at load of 3 mN and speed $U = 0.66$ mm/s in comparison to model predictions of (de Vicente *et al.*, 2005a) lubricated with sunflower oil, showing (a) film thickness map expressed as RGB intensity values indicated in the colour bar, and (b) film thickness profile along centreline. Reproduced from Myant *et al.*, 2010, with permission of Taylor and Francis. For a colour version of this figure, please see Plate 12.1.

exit region that is given by a minimum film thickness, $h_{\min}$. This constriction is often observed as a horseshoe in circular EHD contacts (Hamrock *et al.*, 2004).

Modelling of isoviscous elastic lubrication has focused almost entirely on predicting the central and minimum EHL film thickness following Hamrock and Dowson (1978), and friction is inferred by assuming Couette shear between parallel surfaces having Hertzian diameter (de Vicente *et al.*, 2005a; de Vicente *et al.*, 2006a). However, de Vicente *et al.* (2005a) developed a numerical model that predicts both the friction coefficient and film thickness, taking into consideration both Couette and Poiseuille flow, both of which are present in the contact. Through regression analysis, the results are represented by Equations 12.3, 12.4 and 12.5. Myant *et al.* (2010) recently developed an optical interferometric technique to measure the film thickness in soft contacts, although this was incapable of measuring the characteristics of the side lobes. However, the experimental data for film thickness was reasonably predicted by the de Vicente *et al.* (2005a) model as shown in Figure 12.4. A notable gradient is observed within the Hertzian contact region compared to conventional hard EHL contacts, and in this way the film takes on a 'convergent wedge' shape that is largely responsible for generating fluid pressure and therefore the load-carrying capacity of the contact.

$$h_c = 3.3\bar{U}^{0.6}\bar{W}^{-0.14}R' \quad (12.3)$$

$$h_{\min} = 2.8\bar{U}^{0.66}\bar{W}^{-0.22}R' \quad (12.4)$$

$$\mu_{\text{total}} = \mu_{\text{Poiseuille}} + \mu_{\text{Couette}} = 1.46\bar{U}^{0.65}\bar{W}^{-0.70} + SRR.(3.8\bar{U}^{0.71}\bar{W}^{-0.76} + 0.96\bar{U}^{0.36}\bar{W}^{-0.11}) \quad (12.5)$$

$\bar{U} = \frac{U\eta}{E'R'}$, $\bar{W} = \frac{W}{E'R'^2}$, E' and R' are the reduced elastic modulus and reduced radius defined by $2/E' = (1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2$ and $1/R' = 1/R_{x1} + 1/R_{x2}$ respectively, where E , ν and R_x are the elastic modulus, Poisson ratio and radii in the entrainment direction respectively for the two surfaces.

12.2.4 Limits of hydrodynamic lubrication: Stribeck curve

From the Reynolds equation and hydrodynamic theory, as the sliding velocity is reduced the film thickness also decreases to maintain the pressure field; the magnitude of pressure is proportional to the square of the reciprocal of film thickness (Stachowiak and Batchelor, 2005). However, eventually the film thickness will decrease to such an extent that asperities may interact between the surfaces leading to elevated friction. In this region, the hydrodynamic film still supports most of the load ('partial hydrodynamic lubrication') but it cannot prevent some contact between opposing surfaces. Further decreases in speed, and thus hydrodynamics, effectively leads to contact between the surfaces.

This process is generally presented as a plot of the friction coefficient against a controlling parameter (film thickness or $\eta U/W$) in the form of a Stribeck curve, as shown in Figure 12.5 where W is the load, U is the entrainment speed and η is the viscosity of the fluid in

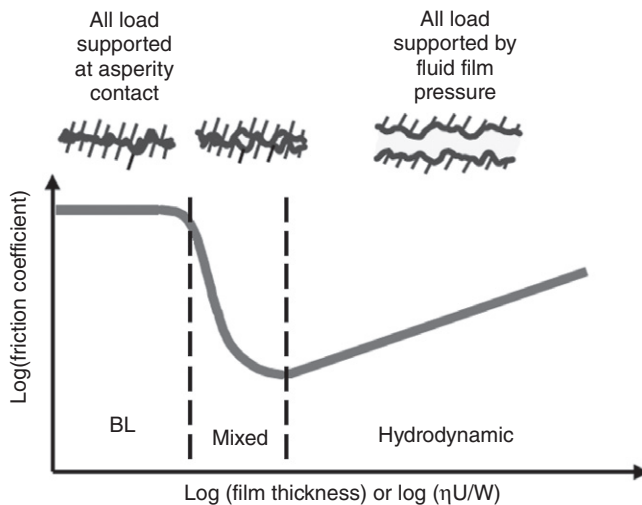


Figure 12.5 Typical Stribeck curve as a function of film thickness or the parameter $\eta U/W$ (η is viscosity, U is entrainment speed and W is load). Reproduced from de Vicente *et al.*, 2006, pp. 483–491, with permission of Elsevier.

the contact (de Vicente *et al.*, 2006b). The lower and higher end of the Stribeck curve are the boundary and hydrodynamic regimes respectively, while the region between these two is referred to as the 'mixed lubrication regime' since it is contributed to by a mixture of hydrodynamics and boundary friction. It has been found that a minimum film thickness of twice the combined roughness of the opposing surface ensures full hydrodynamic lubrication for relatively smooth surfaces (Stachowiak and Batchelor, 2005). In the low-pressure elastohydrodynamic contacts relevant to oral tribology, the dimensionless film parameter (Λ) is reported to range from 2 to 5 in the mixed regime, where Λ is defined (Cassin *et al.*, 2001; Hamrock *et al.*, 2004):

$$\Lambda = \frac{h_c}{\sqrt{\sigma_a^2 + \sigma_b^2}} \quad (12.6)$$

h_c is the central film thickness and $\sigma_{a,b}$ are the rms surface finishes of the interacting surfaces. In engineering contacts involving rough surfaces, even when $\Lambda = 1$, limited wear has been observed which is explained by elastic deformation flattening the asperities. In a recent study using highly deformable surfaces made from polydimethylsiloxane (PDMS), it was observed that entry into the EHD regime occurred at $\Lambda = 11$ for the smoothest surface ($\sigma = 8.6$ nm) and $\Lambda = 0.7$ for the roughest surface ($\sigma = 3.6$ μ m) (Bongaerts *et al.*, 2007b). The deformation of asperities is clearly important for the transitions to each regime when dealing with elastic substrates.

Wetting characteristics of the surfaces also have a major influence on the measured Stribeck curve. Figure 12.6 shows the Stribeck curve for a range of different viscosity Newtonian aqueous fluids between PDMS ball and disk. The surfaces were altered from hydrophobic to hydrophilic using Plasmon treatment. It is notable that hydrophilic surfaces promote full film lubrication so that a lower value of ηU for the mixed-EHL regime transition is obtained in comparison to hydrophobic surfaces. An aqueous film is retained at the hydrophilic surface and is not easily squeezed from the contact at low speeds. This is not the case for hydrophobic surfaces where a friction coefficient that is close to the value for the dry friction coefficient is observed (Bongaerts *et al.*, 2007a). An empirical equation was used to fit the master curve data as follows:

$$\mu = \mu_{EHL} + \left(\frac{\mu_b - \mu_{EHL}}{1 + (\eta U / B)^m} \right) \quad (12.7)$$

μ_{EHL} and μ_b are power law functions of ηU for the hydrodynamic and boundary regimes, B and m are constants.

12.2.5 Boundary lubrication

The boundary lubrication regime occurs at particular operating conditions (e.g. low speeds, high loads or insufficient lubricant) where the pressure from hydrodynamics is insufficient to separate the surfaces, as indicated in Figure 12.5. This regime is dependent on the ability of the fluid's constituents to form boundary films, which is considered below, and tends to arise from surface adsorption of species from the lubricant or localised viscosity enhancement. Boundary lubrication can also arise from the presence of amorphous layers or use of sacrificial films on the substrate (Stachowiak and Batchelor, 2005).

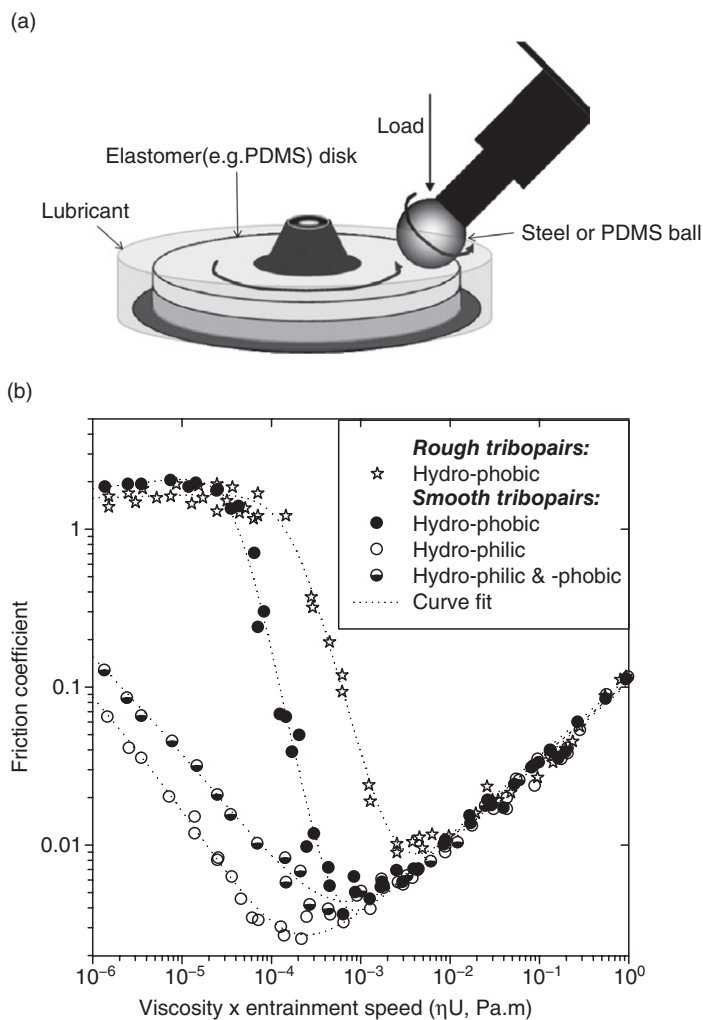


Figure 12.6 (a) Schematic representation of mini-traction machine (MTM) used to study the lubrication properties of food-related lubricants. The device is modified to utilise elastomeric surfaces such as polydimethylsiloxane (PDMS) in place of traditional steel tribopairs. (b) Collection of Stribeck curves showing the influence of surface properties (wetting, roughness) using PDMS ball-disk tribopairs lubricated with a range of aqueous Newtonian fluids varying in viscosity from 1 mPas to 2.8 Pas. Adapted from (Bongaerts *et al.*, 2007a).

Surface adsorption typically involves molecular layer films. While the mechanism of asperity contact is the same as for dry surfaces, the films act by providing a low shear strength interface between opposing surfaces due to repulsion or weak bonding; this is apparent for adsorption of fatty acids or surfactant from oils that strongly bind to metallic surfaces. Physical adsorption (physisorption) involves attachment to the surface by a species without irreversible changes to the surface, and is typically from van der Waals, dispersion forces or other low energy bonding mechanisms. Chemical adsorption (chemisorption) involves irreversible adsorption through chemical bonding between the adsorbate and substrate. The molecular structure of the adsorbate strongly influences the effectiveness of

boundary lubrication. For fatty acids or surfactants at metallic substrates, it is found that linear molecules are best for forming close packed monolayers on the surface with the non-polar tail pointing outwards in the oil lubricant and the polar head group adsorbed to the surface (Bowden *et al.*, 1945; Jahanmir and Beltzer, 1986). There is a strong repulsive force between opposing linear tails when densely packed. Branched molecules are not as effective, due to poor surface coverage, and thus allow greater interaction between opposing layers.

Surface-localised viscosity enhancement is the situation whereby a thin layer of anomalously high viscosity can form on the contact surfaces such that quasi-hydrodynamic lubrication then prevents solid contact (Allen and Drauglis, 1969; Jahanmir, 1985). This is considered to occur for organic molecules, including paraffin and cyclohexane, that can align normally to the contacting surfaces, but it is only effective under low loads and temperatures. A viscous layer is also purported to be the mechanism for the presences of a soap layer at metal hydroxide surfaces due to reaction with fatty acid (Bowden *et al.*, 1945).

These boundary lubrication mechanisms are those considered in the engineering literature that concerns oil based lubricants. While relevant for understanding tribology, aqueous lubrication is more relevant to oral tribology. Aqueous lubrication is emerging as an interesting area for study due to its prevalence in natural systems (Lee and Spencer, 2008). Low friction is considered to arise when sliding occurs at the interface between adsorbed surface layers of surfactant or polymers, or at the substrate interface (Briscoe *et al.*, 2006). For example, the good boundary lubrication properties of extended polymers and polymer brushes arise from their ability to support the applied load and strong anchoring of the polymers onto the tribopair surfaces. Interchain repulsion on opposing substrates and hydration of the polymer can create a fluid-like cushioning layer on the surface and a low viscosity region where polymer chains can easily slide along each other leading to low interfacial friction (Lee and Spencer, 2008). A 'hydration lubrication' mechanism has also been recently proposed to explain the boundary lubricating properties of hydrated ions, as well as hydrated charged polymers and surfactants, when confined between charged surfaces (Briscoe *et al.*, 2006; Raviv *et al.*, 2001; Raviv *et al.*, 2003; Raviv and Klein, 2002). It is suggested that hydration sheaths around confined ions support the normal load and have a fluid-like response under shear due to rapid exchange of water molecules. For surfactants where the polar head group is bound to the substrate, hydration of the head group is thought to create a locally fluid region ('slip' plane) at the surfactant–substrate interface and thus low friction (Briscoe *et al.*, 2006).

12.3 FOOD LUBRICATION

Lubrication has long been considered an important factor in the oral processing of foods (Hutchings and Lillford, 1988; Kokini *et al.*, 1977), although it is only recently that researchers have begun to try to evaluate such properties. It is certainly important in the texture perception of food, since the term 'texture' arises from the feel of fabrics and surfaces which is, in its essence, tribology. The difficulty with foods is that they contain multiple phases and multiple components that are interfacially active, and have complex rheological properties. Another major difference is that oral lubrication involves shearing against deformable rough substrates; this means that the shearing surfaces themselves are compliant (i.e. soft-tribology) and that boundary and mixed lubrication regimes are likely to be important (Bongaerts *et al.*, 2007a). Hence studies into oral tribology and food

lubrication are a new area of tribology research that has not been widely addressed in the tribological literature or textbooks.

12.3.1 Kokini models for 'smoothness' and 'slipperiness'

In assessing foods, Kokini (1987) highlights the fact that the consumer moves their tongue across the food to be judged. For liquids this results in a lubricated contact between the tongue and roof of the mouth, while for solids and semi-solids it is the frictional force between tongue (and/or palate) and food itself. It was postulated that 'smoothness' perception of a food product is related to the reciprocal of the friction force (Equation 12.6). To test the hypothesis, a rubber cylinder covered with chamois was pulled over each food (including cream, milk, whipped butter, ice cream) at constant velocities ranging from 1.27 cm/min to 5.08 cm/min and normal loads of 10–45 g, conditions considered similar to those in the mouth (Kokini and Cussler, 1983). The numbers obtained for the friction force were directly correlated to sensory scores for smoothness, and while a correlation coefficient of 0.82 was obtained, this was heavily reliant on the friction factor of two foods (sherbert and frozen orange juice) and hence the data was inconclusive. A better correlation was found for sugar syrup based liquid foods with biopolymer thickeners (Kokini *et al.*, 1977), as shown in Figure 12.7. 'Slipperiness' perception was postulated to be from the total force on the tongue, which is the summation of viscous force and friction (Equation 12.9).

$$\text{'smoothness'} \propto \frac{1}{\mu W} \quad (12.8)$$

$$\text{'slipperiness'} \propto \frac{1}{\eta \left(\frac{V}{h_s} \right)^n \pi R^2 + \mu W} \quad (12.9)$$

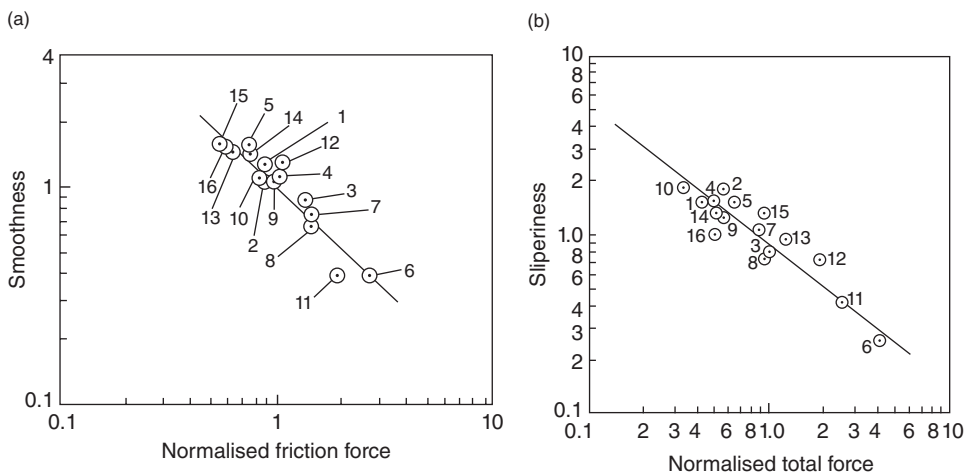


Figure 12.7 Sensory assessments of thickened fluids showing a correlation with measured friction: (a) smoothness versus friction force (Equation 12.8), and (b) slipperiness versus total friction force (Equation 12.9). Reproduced from Kokini *et al.*, 1977, with permission of John Wiley & Sons.

Using sugar syrup based liquids; this was also shown to correlate to a reasonable degree with oral perception of slipperiness, with a correlation coefficient of 0.88. These studies assumed a limited set of speeds and load values, with little consideration of which friction regime the system was in, but the development of these relatively simple measures supported the idea that tribology is important in the mouth and has the potential to be used to add value to food design. Kokini *et al.* (1977) highlighted the dynamic nature of oral processing and the sequential evaluation of textural attributes (texture profiling):

Our work suggests that this sequential evaluation occurs because tactile perception is related to sequential physical events. These events depend on the amount of liquid separating the tongue and the roof of the mouth. Initially, this separation is complete because the tongue is in contact only with the liquid. As a result, the tongue assesses the viscous force associated with 'thickness'. Later, when the tongue begins to touch the mouth, it feels both viscous and friction forces and can assess 'slipperiness'. Still later, the tongue extensively touches the mouth, and so feels almost exclusively the friction force associated with 'smoothness'. Clearly, this overall sequence is only partially represented by the model used above; a more exact sequence still awaiting development should include both a complete description of the tongue movement and the effect of saliva.

There was little effort put into developing an improved model of food-oral lubrication following this pioneering work of Kokini and co-workers. It is only over the last few years that there has been a surge of interest in the field, although we are still a long way off having a predictive capability for sensory textural perceptions based on measurable tribological-related parameters as first postulated by Kokini.

There have been a few measurements performed on full product samples such as chocolate and mayonnaise. For example, the lubrication of molten chocolate samples in a pin-on-disk tribometer is found to depend on particle behaviour at the inlet region of the sliding contact (Lee *et al.*, 2004), while the response in a surface force apparatus depended on fat constitution and average particle size. When mayonnaise samples were confined to narrow gaps in a surface force apparatus, the response also depended on particle properties such as size, stiffness and hydrophobicity (Giasson *et al.*, 1997). However, it is difficult to interpret the tribological response of full product formulations and to determine what needs to be designed into the product to give desired behaviour. Recent approaches have been focused on understanding the tribological properties of model foods using either simulated oral contacts (which could include *ex vivo* pigs tongue) or well-defined tribometer configurations.

12.3.2 Biosubstrates and simulated oral contacts

Various studies on oral processing have indicated that the tongue can move at speeds of up to 200 mm/s (Hiimae and Palmer, 2003) and apply loads of between 0.01 to 90 N (Miller and Watkin, 1996; Prinz *et al.*, 2007). The tongue surface is extremely rough and papillae on the tongue are of the order of 100 microns in height and diameter (Ranc *et al.*, 2006). The elastic modulus of a pig's tongue has been measured to vary with location and thickness of cylindrical sample, with values ranging from 0.7 to 3 kPa (Dresselhuys *et al.*, 2008a). It is suggested that the actual value of the papillae modulus *in vivo* is lower because of the hardening of muscular tissues *ex vivo* from rigour mortis (van Aken, 2010). These highlight the high deformability of oral tissues, which is quite unlike those extensively studied in tribological applications in engineering.

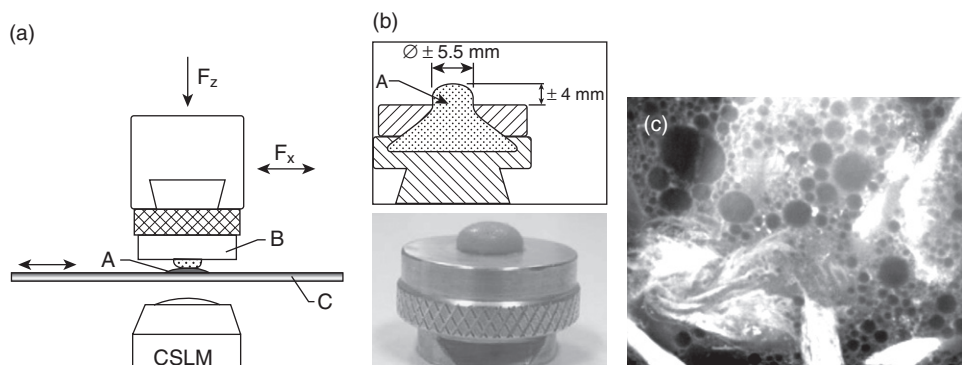


Figure 12.8 (a) Optical tribological configuration, showing emulsion (A) confined between an upper surfaces (B, e.g. pigs tongue, PDMS) and a glass surface (C). Friction force (F_x) is measured while oscillating surface C under a normal force (F_z). (b) Measurement probe (B) with a tongue sample screwed into the probe. Reproduced from *Food Hydrocolloids* **22**:2, Dresselhuis *et al.*, 'Application of oral tissue in tribological measurements in and emulsion perception context', pp. 323–335 (2008). With permission from Elsevier. (c) Image of emulsion droplets (black spheres) between papillae (white strands) of a pig's tongue. Reproduced from van Aken *et al.*, 2007, pp. 251–262, with permission of Elsevier.

There have been several studies attempting to understand and probe the response of model food systems, such as emulsions, in simulated oral contacts utilising biosubstrates, such as between a pigs tongue and oesophagus (de Hoog *et al.*, 2006; Prinz *et al.*, 2007) and pigs tongue and glass surface (Dresselhuis *et al.*, 2007, 2008a; van Vliet *et al.*, 2009). These have indicated that there is potentially a relationship between friction force measurements, in-mouth coalescence and fat perception (Dresselhuis *et al.*, 2008a). In experiments utilising a pigs tongue and oesophagus, the high deformability of the papillae on the tongue surface allowed it to flatten under load so that similar lubrication behaviour was found for model emulsions on glass–rubber surfaces (de Hoog *et al.*, 2006).

A novel tribological setup was developed by Dresselhuis *et al.* (2008b) to measure the lubricated sliding friction on a pigs tongue whilst imaging the contact with a confocal scanning laser microscope; the configuration is shown in Figure 12.8. A piglet's tongue was used because it was considered to have a closer degree of keratinisation to the human tongue. The dried tongue surface was found to be intrinsically hydrophobic, but was hydrophilic if coated with mucous fluids (Dresselhuis *et al.*, 2008b). A major finding of their studies in food emulsions was that oil droplet coalescence occurred between the papillae, and that in general oil is released from the emulsion. However, using pig's tongues was found to be difficult due to alteration of the tongue structure and material properties during long term storage, and only limited experiments could be conducted due to direct contact between the tongue surface and glass slide causing wear.

To circumvent the need to use a real tongue surface, Ranc *et al.* (2006) fabricated surface structures on silicone elastomer (PDMS) that resembled the roughness of the tongue. The fabricated surface consisted of hemispherical pillars of varying diameter (100 μm and 250 μm), height (50–250 μm) and surface density. However, only limited measurements have so far been made using a reciprocating motion sliding tribometer and only a narrow set of food emulsions tested (Bellamy *et al.*, 2009).

The main conclusions from these limited studies using simulated oral substrates are that the tribological tongue–palate contact is essentially in the mixed lubrication regime. The high roughness and compliance of the tongue substrate ensures that contact is made during rubbing (i.e. boundary lubrication), but shear of the lubricant can also take place between the asperities. Future research needs to develop a greater understanding of this complex process and this may require more sophisticated tribology measurements over a greater range of speeds and loads, as well as the use of fabricated surface structures with controlled surface chemistry to probe the influence of topology following the work of Ranc *et al.* (2006) in combination with the *in situ* visualisation demonstrated by Dresselhuis *et al.* (2008b).

12.3.3 Soft-tribology

There have been a variety of approaches to characterise the lubrication properties of model foods, but most of these only use a narrow set of speeds and loads such that little information is gleaned about mechanisms for observed friction response. The most comprehensive studies to determine how the different properties of foods may affect lubrication performance have been those using a mini-traction machine (Figure 12.6) consisting of a ball-disk in relative motion (typically a combination of sliding and rolling). This device has been used because it had already been well-studied in the tribological literature, and the only modification required was the replacement of steel tribopairs with elastic substrates. Other tribological configurations attempted include o-ring covered cylinders (Chojnicka *et al.*, 2008) and tribology fixtures on rheometers (Goh *et al.*, 2010), but these are yet to be well validated using model fluids or theoretical analysis, which makes it difficult to interpret results, and they are therefore not considered here.

12.3.3.1 Master curves

One of the key lubricant properties that govern friction is fluid viscosity. This is demonstrated in Figure 12.9 (also see Figure 12.6) where measured friction coefficient is displayed

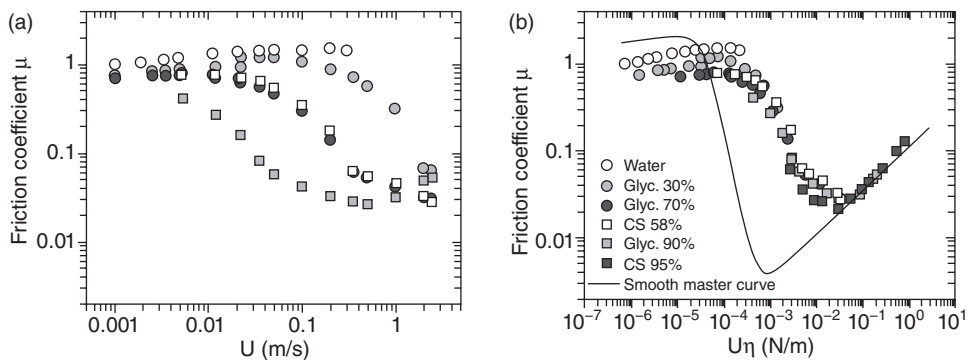


Figure 12.9 Influence of viscosity on the lubrication of aqueous fluids on relatively roughness surfaces (382 nm rms) and presentation as a 'master curve'. Friction coefficient is shown against (a) entrainment speed, and (b) ηU , where the solid line is the master curve for smooth surfaces (9 nm rms). Reproduced from Bongaerts *et al.*, 2007, pp. 1531–1542, with permission of Elsevier.

for different viscosity aqueous Newtonian fluids between a ball-disk PDMS tribopair in a mixed sliding-rolling contact with a disk surface roughness (rms) of 382 nm. Due to the relatively rough nature of the surface, most of the data is in the boundary and mixed regime, whereby increases in viscosity decrease the friction coefficient. At a constant load, multiplying the entrainment speed by the lubricant viscosity (i.e. ηU) shifts the data onto a single master curve over the mixed and hydrodynamic regimes. It is important to note that at low speeds where asperities are contacting in the boundary regime, the friction coefficient is mainly dependent on the speed rather than ηU , although the boundary friction coefficient does seem to be lower for the higher viscosity fluids.

The utilisation of a master curve is important when examining the lubrication of food systems. Foods are complex rheologically and contain multiple phases, hence it can be difficult to determine the controlling mechanism for the measured friction coefficient. It was found by Bongaerts *et al.* (2007a) that the friction coefficient in the hydrodynamic regime using hydrophilic and hydrophobic (rough and smooth) substrates followed the same ηU dependency. Hence, provided a portion of the hydrodynamic regime is measured, the viscosity of any fluid in the contact region can be determined without the need to know the shear rate or film thickness.

12.3.3.2 Emulsions

Emulsions have received considerable attention in oral tribology literature due to the association between fat and various textural attributes. As Figure 12.1 shows, tribometers can be used to distinguish differences between low fat and high fat food products, like mayonnaise, that don't have discernable differences in rheology. Malone *et al.* (2003) reported the lubricating properties of complex emulsions comprising hydrocolloid thickener, surfactant and sunflower oil between a steel-elastomer tribopair. While they were viscosity matched at a shear rate of 50 s^{-1} , the Stribeck curves varied with oil and thickener content as shown in Figure 12.10. The sensory data showed that fattiness perception correlated well

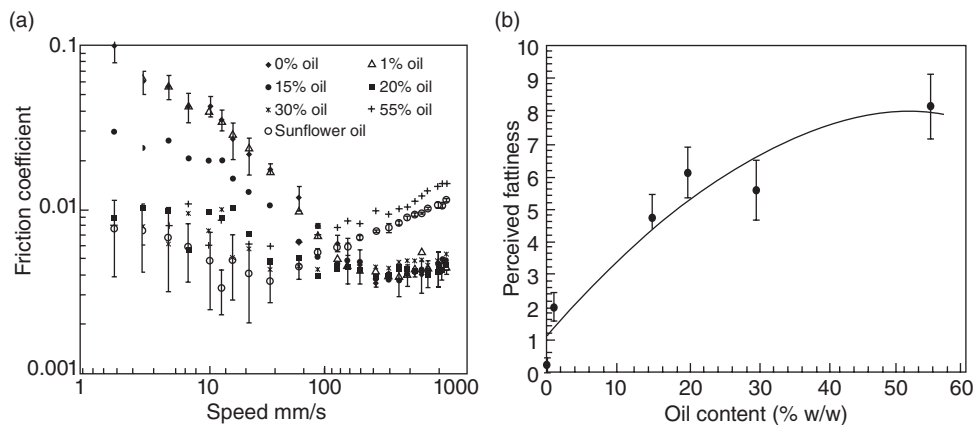


Figure 12.10 (a) Friction coefficient measurements in an MTM between a steel ball and elastomer disk for a range of food o/w emulsions that differed in oil and thickener content so that they were isoviscous at a shear rate of 50 s^{-1} . (b) Sensory panel data on fattiness perception for the same emulsions. Reproduced from Malone *et al.*, 2003, pp. 763–773, with permission of Elsevier.

with oil content, but panellists found it hard to distinguish between the 15–30% oil samples; it was suggested that this matched expectation from tribology measurements. However, while these studies demonstrate that tribology can detect differences in food emulsions, they do not inform us on the mechanisms of lubrication, which makes it difficult for rational design of low-fat foods.

Since foods contain a large range of ingredients with different rheologies, it is necessary to understand how these different viscosity phases will affect the Stribeck curve. When tribopairs have matching wetting properties, it is found for emulsions without surfactant that the oil is preferentially entrained between hydrophobic tribopairs, and the aqueous phase is entrained between hydrophilic tribopairs regardless of the viscosity ratio (Bongaerts and Stokes, in prep.). However, when surfactant is present or mixed-tribopairs are used, then the viscosity ratio along with surfactant adsorption (which alters the surface wetting characteristics) play pivotal roles. De Vicente (2006) used mixed tribopairs to show the importance of the viscosity ratio ($p = \eta_{\text{oil}}/\eta_{\text{water}}$ for o/w emulsions) for surfactant-free emulsions containing 20% oil; at $p \geq 5.8$, the sunflower oil dominates film formation and friction, while at $p \leq 1.3$, the thickened aqueous phase dominates the friction. Surfactants influence emulsion lubrication properties by adsorbing to the substrate to change wetting characteristics; this allows, for example, oil to wet hydrophilic steel surfaces (Cambiella *et al.*, 2006). Oil drop size is also of critical importance to the lubrication of emulsions; droplets that are smaller than the surface roughness do not contribute significantly to the lubrication properties of the emulsion (Graca *et al.*, 2009), but droplets larger than the roughness and EHD film thickness are preferentially entrained into the contact zone to dominate the friction coefficient. In tribology EHD literature, oil is often observed to preferentially form lubricating films, but this is in emulsions without added thickening agents. The common model utilised to explain this observation is that as the emulsion moves through the supply region, the film thickness is such that the oil droplet can bridge the gap between the surfaces and become attached to, or wet, the surfaces, as shown in Figure 12.11. At this point the emulsion enters the concentration zone and is difficult to displace (Wilson *et al.*, 1994). In tribology literature, low surfactant concentrations can be used to ensure surfactant adsorption to hydrophilic steel surfaces and to create unstable emulsions that then allow oil to be entrained in the contact (Barker *et al.*, 1993; Cambiella *et al.*, 2006; Ratoi-Salagean *et al.*, 1997).

Dresselhuis *et al.* (2007, 2008b, 2008c) investigated the adhesion, wetting and spreading of protein-stabilised emulsions at surfaces varying in hydrophobicity on a porcine tongue. Emulsion droplets stabilised by low amounts of protein are more prone to adhere and spread on tongue and hydrophobic surfaces than more stable emulsion droplets stabilised with high

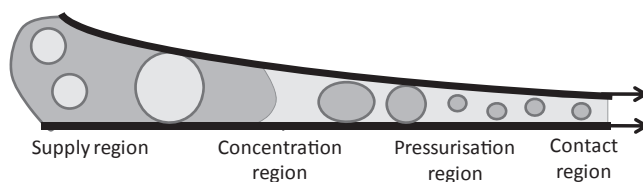


Figure 12.11 A pictorial representation of the mixed flow model for emulsion lubrication showing the oil phase from an o/w emulsion being concentrated between shearing surfaces (Wilson *et al.*, 1994). Deviations from this model occur upon altering surface properties (wetting, roughness), drop size, and surfactant type and concentration.

amounts of protein (Dresselhuys *et al.*, 2008a). The adherence and spreading of protein-stabilised emulsion droplets on hydrophobic surfaces was also visualised in a flow cell, and it was considered that adhesion arose from hydrophobic attraction at short distances due to decreased electrostatic and steric repulsive forces (Dresselhuys *et al.*, 2008c). When the solid surface was rendered hydrophilic, the emulsion droplets barely adhered and did not spread. Saliva is observed to play only a minor role in this emulsion drop adhesion and spreading process. However, it was observed that saliva can interact with droplets to remove them from the surface (Dresselhuys *et al.*, 2008c).

Dresselhuys *et al.* (2008a) also evaluated the sensory properties of stable and unstable emulsions, stabilised using protein, octenylsuccinate starch (OSA) or solid fat. A particularly novel aspect was the use of OSA to form stable emulsions in storage that become unstable in-mouth because amylase in saliva breaks down the starch. Emulsions with a higher sensitivity towards coalescence were perceived as most fatty and creamy, and these also gave lower friction forces. Other sensorial attributes such as aroma release and mouth-feel were also affected by the emulsion stability. It is suggested that this may be a route by which to control in-mouth behaviour and perception of emulsions.

12.3.3.3 Hydrocolloids

Hydrocolloids such as polysaccharides are present in many food systems, and various studies have examined their lubrication properties in aqueous solution. Their potential importance to understanding the sensory properties of foods was highlighted by Malone *et al.* (2003) who considered that 'oral slipperiness' perception of guar solutions was related to the mixed regime friction coefficient between a steel ball and rough-elastomeric plate (Figure 12.12). This was essentially suggested by Kokini, who considered oral slipperiness to arise from a combination of friction and viscous effects; this is precisely the case for the friction coefficient in the mixed regime. Polysaccharides and other polymers lower the friction coefficient with increasing concentration in the boundary-mixed regimes in sliding/rolling contacts. This is brought about by two effects: first increasing viscosity with increasing concentration, and/or second physical adsorption of the polymers to the substrates.

Polysaccharides are used as thickening agents and the viscosity at low shear rates is typically several decades above that of water. However, tribological contacts involve narrow gaps between the rubbing surfaces, which suggests that shear rates are well above 1000 s^{-1} ; this is about the limit of standard rheology measurements (de Vicente *et al.*, 2005b, 2006b). Narrow-gap parallel plate rheometry allows the rheology of polymer solutions to be measured at shear rates as high as 10^5 s^{-1} (Davies and Stokes, 2008). It is found that while polymer solutions may have similar low-shear rheology, they can differ markedly at shear rates exceeding 1000 s^{-1} in terms of both viscosity and elasticity (e.g. normal stress differences). The viscosity at shear rates of around 10^4 to 10^5 s^{-1} accounts for most of the decrease in friction coefficient in the mixed-regime, as demonstrated for a synthetic polymer in Figure 12.13. The lateral shift in the Stribeck curve for the polymer solutions is the contribution from the polymer adsorption to the substrate.

Polysaccharides and other polymers have the potential to adsorb to surfaces, which modifies the surface properties of the substrate and provides the potential for a boundary lubricating film. There are several mechanisms proposed by which polymers in aqueous media behave as effective boundary lubricants, as previously highlighted in the section on boundary lubrication. It has been recently shown that the boundary and mixed lubrication properties of polysaccharides are directly related to the adsorbed film mass and hydration.

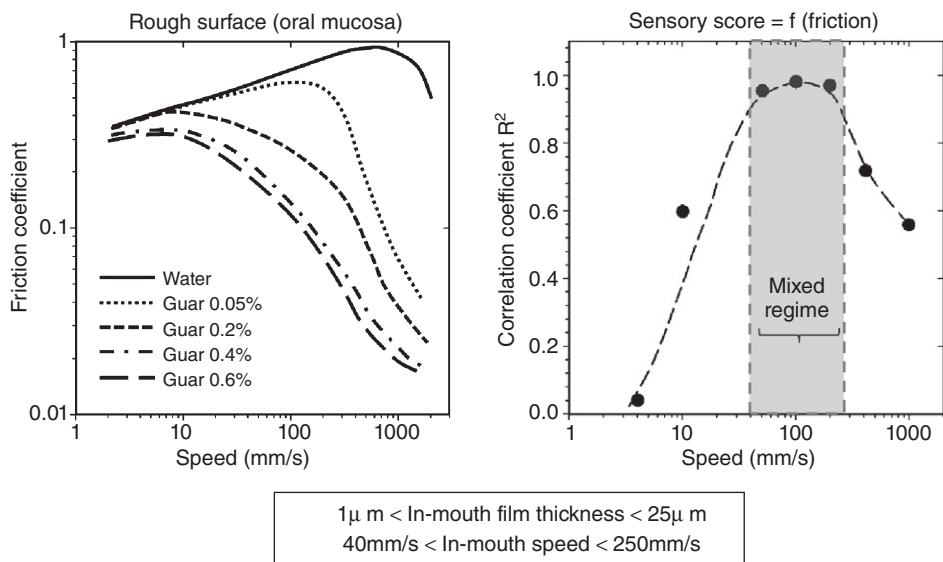


Figure 12.12 (a) Stribeck curve for guar gum solutions measured using an MTM with a steel ball and elastomer disk at 35 °C. (b) Correlation coefficient for 'oral slipperiness' when a linear regression is made to friction measurements for each speed. The best correlation was found around 100 mm/s which indicates that the mixed regime is most relevant. Reproduced from Malone *et al.*, 2003, pp. 763–773, with permission of Elsevier.

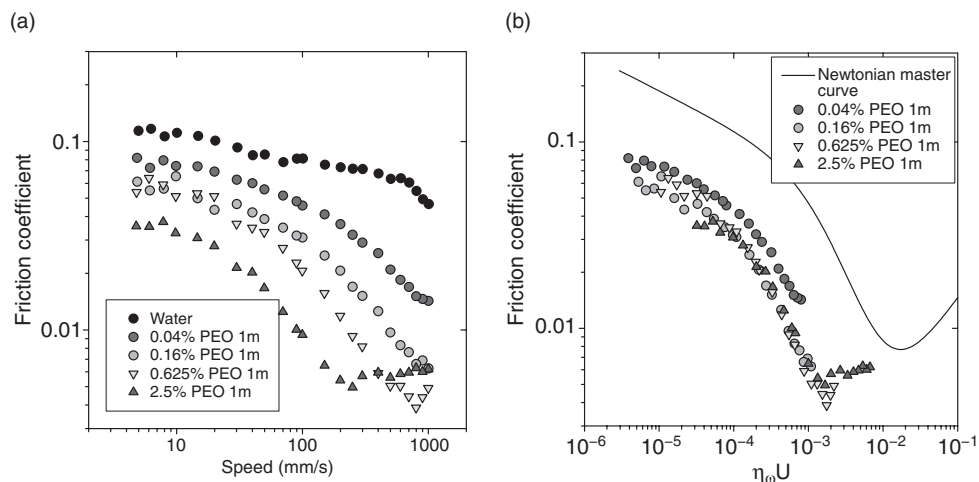


Figure 12.13 Stribeck curves for 1 million molecular weight polyethylene oxide solutions in water between steel ball and elastomer disk at 35 °C and 1.3 N load, showing friction coefficient (a) against speed (adapted from (de Vicente *et al.*, 2005b), and (b) $\eta_\infty U$, where η_∞ is shear viscosity evaluated at 10^5 s^{-1} and the line represents the master curve for aqueous Newtonian fluids (Davis and Stokes, 2008). The overlapping of the data indicates that most of the friction coefficient in the mixed regime is from the viscosity of the solutions in the tribological contact.

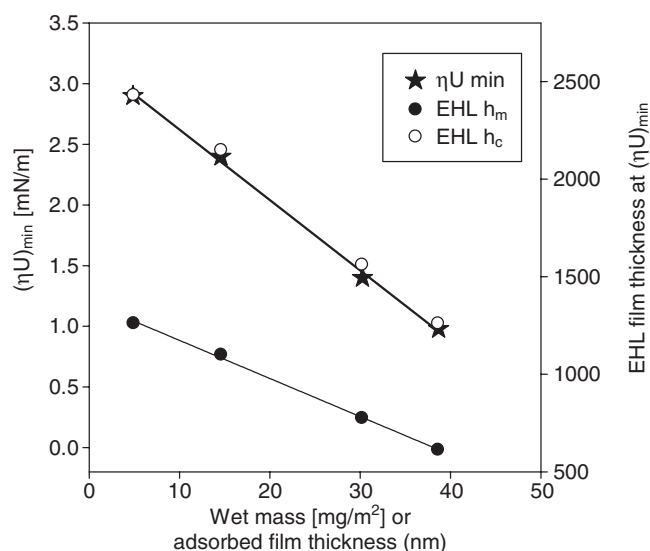


Figure 12.14 Correlation shown between friction measurements on the MTM using a PDMS–PDMS tribopair and adsorbed film properties obtained from quartz crystal microbalance: $(\eta U)_{\min}$ corresponds to the value of ηU at the minimum friction coefficient (transition from mixed to EHL regime); h_m and h_c correspond to the minimum and central film thickness calculated using Equation 12.3 and 12.4; the wet mass is mass of polymer and any water associated with it (also equivalent to an adsorbed hydrated film thickness). The data points from left-to-right correspond to locus bean gum, xanthan, gellan and pectin. Adapted with permission from Stokes *et al.* 2011, pp. 3474–3484, copyright 2011 American Chemical Society.

In particular, the value for $\eta_{\infty}U$ (for constant load) where the friction coefficient is a minimum, which corresponds to the transition between the mixed and hydrodynamic regime, is inversely related to the adsorbed film's wet mass or hydrated thickness (Stokes *et al.*, 2011), as shown in Figure 12.14. The novel relationship was obtained using four different polysaccharides, with locus bean gum and pectin being the least and most effective respectively of those tested. Uncharged locus bean gum adsorbed in the form of a thin rigid film where its limited effectiveness as a boundary lubricant is ascribed to its inability to retain water in the contact zone. However, anionic high methoxy pectin adsorbed as a highly viscoelastic and hydrated film that was able to sustain a load and retain water in the film whilst also being resistant to wear (Stokes *et al.*, 2011).

12.3.3.4 Saliva

One of the main functions of saliva is to provide a lubricating film on oral surfaces. This is exemplified by people with impaired saliva production or quality (xerostomia, dry mouth syndrome) that suffer from a variety of symptoms including problems with mastication, swallowing and speech as well as from more rapid wear of their teeth. Saliva is present in the oral cavity as both a bound layer (e.g. pellicle on teeth) and as a mobile film. It has a unique ability to adsorb onto substrates of practically any chemical nature in the form of a multi-component protein-rich film (Cardenas *et al.*, 2007; Macakova *et al.*, 2010).

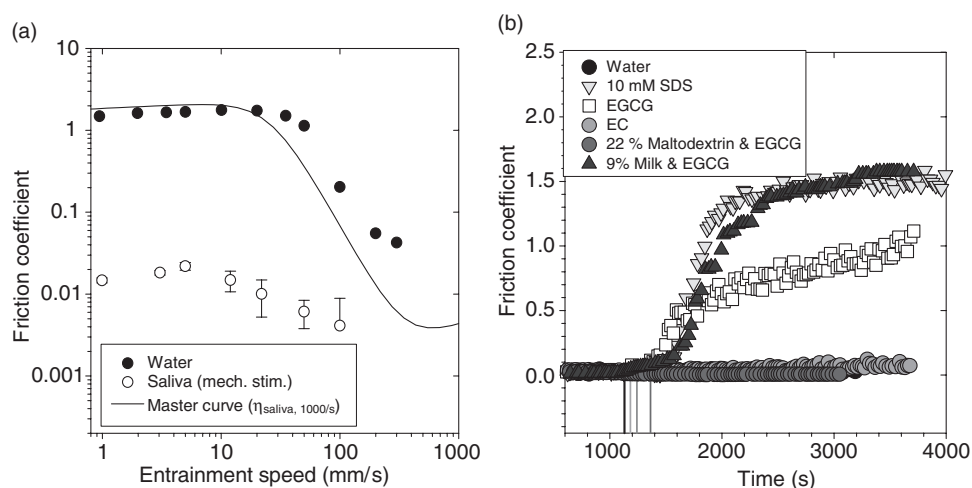


Figure 12.15 (a) Stribeck curve for mechanically stimulated saliva measured using an MTM at 35 °C between PDMS ball and disk at a load of 1 N. Also shown are water and a friction curve calculated based on the master Stribeck for non-adsorbing aqueous fluids at the viscosity of saliva (at 1000 s⁻¹). Adapted from (Bongaerts *et al.*, 2007b). (b) Friction coefficient (at a speed of 5 mm/s) of saliva-coated PDMS. After a run in time of ~1200 s, the surface is exposed to various solutions including EGCG and EC tea catechins. Adapted from Rossetti *et al.*, 2009.

The lubrication properties of saliva have been characterised by adsorbing saliva to hydrophobic PDMS substrates (Bongaerts *et al.*, 2007b; Rossetti *et al.*, 2009). A friction coefficient of order 0.01 is observed in the boundary-mixed lubrication regime that is relatively constant with speed (Figure 12.15). The surface film is viscoelastic and highly hydrated, with a heterogeneous structure consisting of an anchoring sublayer, which contains small salivary proteins and non-glycosylated parts (hydrophobic, 'naked' polypeptide region) of large glycoproteins, and a lubricious outer layer consisting of glycosylated hydrated chains (hydrophilic region) of the glycoproteins (Cardenas *et al.*, 2007; Macakova *et al.*, 2010). The essential glycoproteins incorporated in salivary films are most likely mucins, which are amphiphilic molecules with partly negatively charged glycosylated chains (Oppenheim *et al.*, 2007; Yakubov *et al.*, 2007).

The observed low friction coefficient can be understood in the context of other highly hydrated polyelectrolyte structures in good solvents, whereby a low interpenetration between surface layers provides a low viscosity region for shear and energy dissipation leading to a low friction coefficient. The presence of salt ions under oral physiological conditions allows some screening of the charges on the polymer chains, thus preventing bridging between tribopairs related to the electrostatic attraction between opposite charges (Macakova *et al.*, 2010). Changing the solvent conditions such as salt concentrations alters the hydration, interpenetration and boundary lubrication properties of the *in vitro* saliva films. Such changes in the saliva film may have implications to the processing and mouth-feel of foods and beverages.

Saliva adsorbed to hydrophobic PDMS substrates was proposed as a potential mimetic for oral substrates in the sensory assessment of beverages. The adsorbed salivary film is found to be particularly robust and wear resistant, as well as responsive to its environment (Rossetti *et al.*, 2009). This oral mimetic was used to assess the mechanism of oral

astringency perception. Astringency is the dry puckery sensation experienced in the mouth upon consumption of wine and tea as well as certain fruits and vegetables, and is considered to arise from phytonutrients such as plant-based polyphenols (catechins). Complexation is thought to occur between saliva and the astringent compounds and leads to precipitation of proteins from saliva, which leads to an increase in friction on the oral cavity due to a loss of lubrication. To test this hypothesis, the oral mimetic was exposed to astringent epigallocatechin gallate (EGCG) catechin solutions at a single speed and load in the tribometer and a significant increase in friction was observed (Figure 12.15). The addition of a hydrocolloid thickener to the catechin solution lowered the friction coefficient and the astringency sensation; both of these support the hypothesis that astringency is related to a loss of lubrication. However, when the salivary film was exposed to epicatechin (EC), a low friction coefficient was maintained although EC solutions were also perceived to be astringent. It was concluded that the ‘the depletion of saliva lubricating proteins is not necessary to obtain an astringent perception, and that astringency is unlikely to be a purely tactile percept’ (Rossetti *et al.*, 2009).

The rheological properties of saliva may also play a major role in saliva’s lubricating properties (Stokes and Davies, 2007; Davies *et al.*, 2009). Curiously, saliva has a very low viscosity that is around 2 mPas at a shear rate of 1000 s^{-1} . Hence its viscosity does not contribute to saliva’s ability to lubricate hydrophobic substrates as described above, nor in the hydrodynamic regime where it would be expected (based on shear viscosity alone) to exhibit similar lubricating properties to water were it measurable (Bongaerts *et al.*, 2007b). However, despite its low viscosity, saliva is extremely viscoelastic, as characterised by its extensibility (i.e. ‘stretchiness’) and measurable normal stresses in shear flow. Saliva’s incredible viscoelasticity results in a normal stress to shear stress ratio of the order 100 for acid-stimulated saliva, meaning that normal forces are 100 times greater than shear forces in flow; this may have ramifications on hydrodynamic lubrication that are yet to be evaluated. In addition, saliva plays a major lubricating role between solid foods and the oral cavity; the low viscosity of the fluid makes an ideal ‘slip’ layer for objects to slide along oral surfaces while the viscoelasticity may assist this process, and the adsorbed saliva film on oral surfaces provides an additional layer of protection and lubricity. This property of saliva is also yet to be examined experimentally.

12.4 CONCLUDING REMARKS

The tribological processes occurring in mouth are unique, and there is still much to learn and discover in this field. A challenge not yet realised is to capture experimentally the highly deformable nature of tongue papillae and determine how this may influence the lubrication behaviour of foods and how it may translate into a sensory percept. Van Aken (2010) considers this question theoretically by modelling the influence of the deformable tongue papillae using a soft-lubrication model (Skotheim and Mahadevan, 2004), and discusses how this may relate to the response of mechanoreceptors buried in oral surfaces. Obtaining one-to-one correlations between tribology measurements and sensory studies has been attempted several times, but while these indicate potential relationships between the two there is still no well-established approach or method that is reliable enough to allow *in vitro* measurements to be mapped onto a sensory response. Most published tribological studies have focused on model foods, which has been necessary as a bottom-up approach to understanding the role of particular ingredients and phases in tribological processes. Future

studies need to build in the complexity of real food systems. In addition, how saliva influences the tribology of foods and food components still needs further attention. It is clear that tribological processes are important to oral processing, and while much progress has been made over the last few years, we are really only at the early stages of understanding oral tribology.

ACKNOWLEDGEMENTS

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13 Applications of Electromyography (EMG) Technique for Eating Studies

Yadira Gonzalez Espinosa and Jianshe Chen

13.1 INTRODUCTION

In vivo characterisation of an eating process is not an easy task due to the challenges of oral access, physiological individuality and particularly the continuously changing food properties throughout the process. Electromyography (EMG) is one of only a few instrumental techniques which are feasible for such purposes. This non-invasive technique is capable of monitoring and recording the electrical activities of the orofacial muscles associated with eating. Pierson and Le Magnen (1970) and Boyar and Kilcast (1986) were pioneers in applying EMG to eating studies in relation to sensed textural properties. Since then, EMG studies have been applied by food researchers in texture and oral behaviour studies. The technique has proved to be reliable and efficient in determining factors that influence human mastication and in relating masticatory parameters to food textural properties. The main challenge in applying EMG techniques to eating studies lies in the standardisation of experimental practices and data analysis to ensure that results obtained from different subjects or from different research groups are comparable. This chapter will review experimental practices and procedures of EMG applications in eating studies. Surface electromyography technique (sEMG) will be the main focus of the review. Issues such as experimental procedures, data analysis and influencing factors will be addressed.

13.2 PRINCIPLES OF ELECTROMYOGRAPHY TECHNIQUE

13.2.1 Muscle motors and their activation

Chewing muscles are those responsible for jaw and tongue movements and for mastication. Like all other body muscles, each chewing muscle possesses hundreds of motor units which become activated during eating. A motor unit consists of a single nerve fibre (neuron) and all of the muscle fibres it innervates. These fibres contract when the action potential (impulse) of the motor nerve reaches a depolarisation threshold. The number of fibres that are controlled by the motor neurons correlates highly with the function of the muscle. Muscles generating large forces have a relatively larger number of muscle fibres per motor unit compared to those muscles responsible for discrete and finer movements. For example,

extraocular muscles have about 5–6 muscle fibres per motor unit for fine control of eye movements, while large muscles of the lower limb, such as gluteus maximus and gastrocnemius, have over 2000 muscle fibres per motor unit, allowing only relatively coarse control of movements.

Action potentials are short-lasting events in which the electrical potential across cell membrane rapidly rises and falls. Unequal flows of ions through the voltage-gated ion channels embedded in the membrane are the cause of membrane potential changes (see Figure 13.1). At rest sodium ions are pumped out of the cells, while potassium ions are pumped in. However, the outward rate of sodium ions exceeds the inward rate of potassium ions (at a ratio of about 3Na^+ out to 2K^+ in). Therefore a potential difference across the cell membrane is established, giving the interior of the cell about -70 mV potential with respect to the outside, known as the resting potential (Figure 13.1A). When a cell is stimulated the permeability of the cell changes causing Na^+ channels open, allowing influx of Na^+ ions (Figure 13.1B). Once the potential reaches a threshold value (around -55 mV), the ion channels will open further, allowing increased inward flux of Na^+ ions. Concentration of positive ions becomes greater inside the cell than outside and the potential across the cell membrane becomes positive 30 mV . This process is known as depolarisation (variation in cellular potential with time) or action potential and lasts for only few milliseconds (Figure 13.1C). After that, Na^+ channels close and K^+ channels open. Gradually the cross membrane potential reverses back to its resting potential of -70 mV .

The action potential generated by muscle motors can be measured by EMG as a voltage. This is done using a pair of electrodes placed either on the surface of the skin above the muscle or inserted into the muscle of interest. The measured EMG signal is therefore the sum of all the individual muscle motor unit action potentials (MUAPs) within the pick-up area of the electrode.

13.2.2 Surface electromyography vs. intra-muscular electromyography

There are two different types of electromyography: surface electromyography (sEMG) and intra-muscular electromyography. The former detects muscle activation by placing electrodes on the skin overlaying the target muscle to record action potentials, while the latter requires the insertion of needle probes directly into the muscle fibres. Intra-muscular electromyography has great advantages in detecting the activities of small muscles that would be impossible with a surface electrode due to cross-talk.¹ A needle probe has incomparable advantages in reaching deep muscles and in isolating specific parts of large muscles and therefore allows a more specific signal pick-up. However, the insertion of needles causes inevitable discomfort to the subject and therefore can alter the subject's chewing behaviour. Moreover, needle insertion also involves risks of tissue damage. In practice, the exact location of needle electrodes is always very difficult to repeat in different tests. Thus intramuscular reproducibility is normally low.

In contrast to needle penetration for intra-muscular electromyography, sEMG only requires skin contact for detecting electrodes. Its non-invasive nature makes it a more comfortable method and a preferred technique for studies of chewing muscles. Surface electromyography has the advantage of easy accessibility of target muscles and convenience of experimental set-up (e.g. no need of electrode sterilisation, no need for medical training

¹Cross-talk refers to the EMG signals detected by the electrode site that comes from neighbouring muscles (muscles adjacent to the muscle being recorded or deeper muscles).

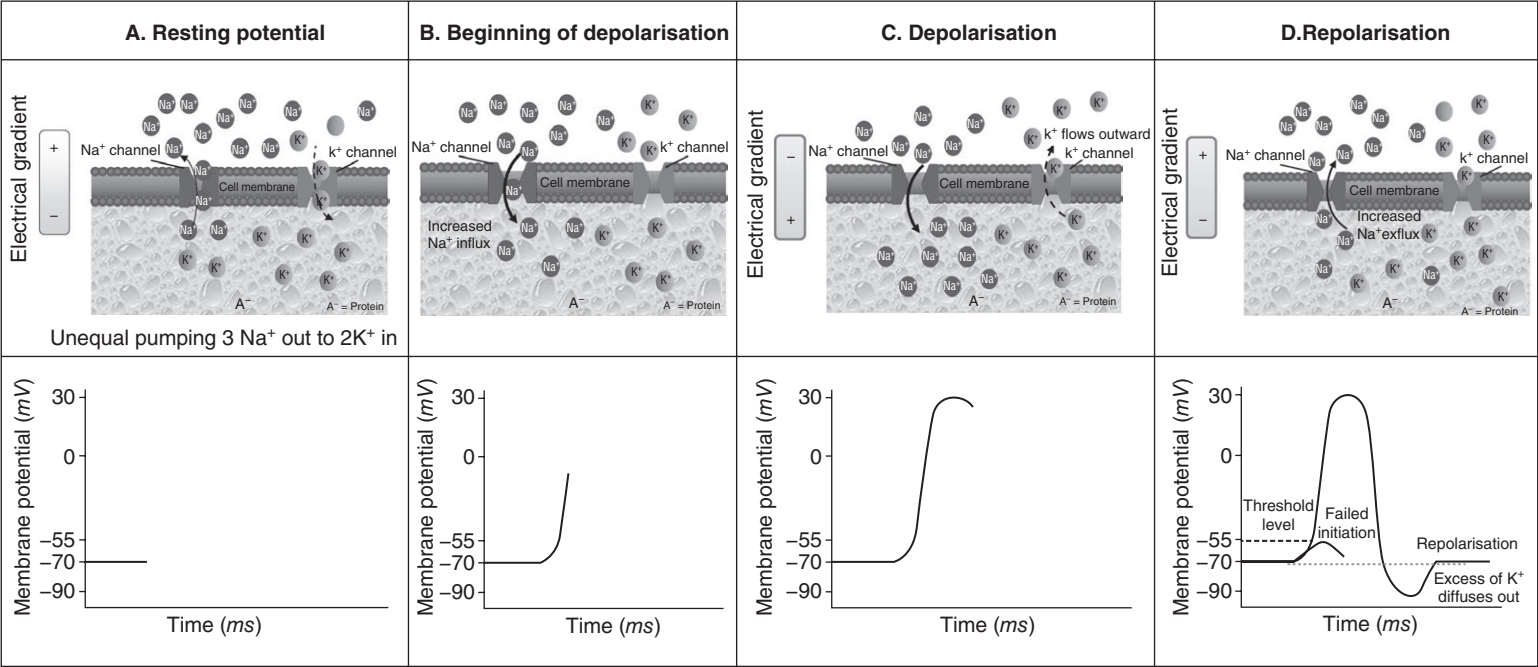


Figure 13.1 Generation of action potentials in cells (see text for details).

of experimenters), though deep buried muscles or muscles under thick skin could sometimes be problematic for this technique. Therefore, sEMG will be the main focus in the following discussion.

The main constraint in the use of the EMG technique is that different practices have been adopted by different researchers and their results are not easily comparable. In a big effort to standardise EMG applications, the International Society of Electromyography and Kinesiology (ISEK) introduced a series of standards for conducting EMG tests and data reporting. These standards provide researchers with some technical guidance that must be taken into account in order to obtain reliable information about muscle behaviour. These considerations include the types of electrodes (e.g. surface electrodes, intra-muscular wire electrodes or needles), electrode preparation, detection, amplification, EMG data processing and analysis.

13.3.3 Main mastication muscles for surface electromyography studies

A great number of muscles are involved in a mastication process. However, only some of these muscles produce strong enough electrical signals for EMG detection. Of these muscles, the masseter lying just beneath the cheeks and the temporalis situated below the temporal fascia are the most superficial muscles that can be conveniently detected through palpation, and their electrical activities can be easily recorded. Both muscles are of good size and belong to the group of jaw-elevator muscles (Figure 13.2), responsible for mouth closing and creating biting forces. Agrawal and collaborators (1998) reported that the temporalis muscles give a burst of activities with both a clear onset and offset during jaw

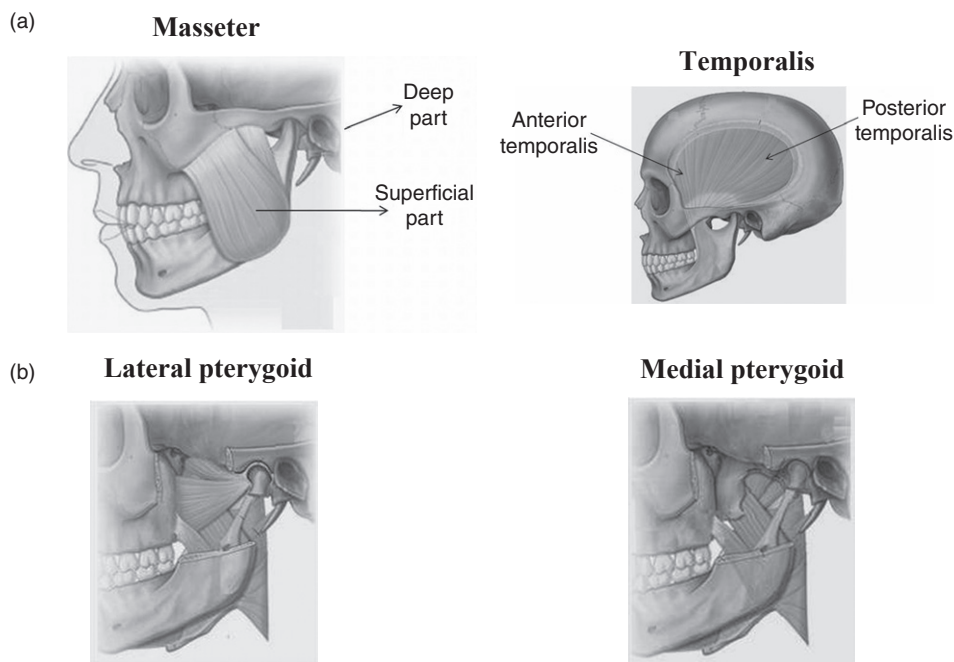


Figure 13.2 Jaw elevator muscles: (a) Superficial muscles that are most easily accessible by surface electromyography; (b) Deeper closing muscles not suitable for recording by surface electromyography.

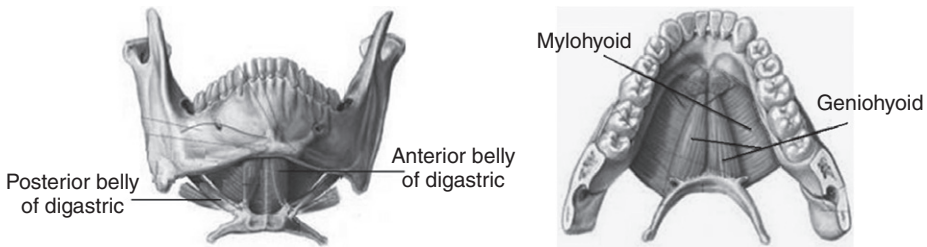


Figure 13.3 Suprahyoid muscles that work synergically for mandibular depression.

closing and a clear EMG silence during mouth opening. They also reported that the recording of the masseter site gives smaller signals with less clearly defined activity and sometimes with cross-talk from other muscles such as platysma and buccinators which are also active during mouth opening.

From the group of mandibular depressor muscles, the anterior belly of the digastric muscle is often recorded. This muscle forms part of the suprahyoid muscles (Figure 13.3) normally known as the submental muscle group, which also include the stylohyoid, the mylohyoid and the geniohyoid muscles, all covered by the platysma. All these muscles act simultaneously when the mandible depresses, therefore EMG recording is unable to differentiate activities between these muscles. However, in such cases the output of the recorded signal contributes to the same action (mandibular depression) and therefore should not represent a major problem when evaluating mandibular opening. Winnberg and Pancherz (1983) suggested that, even though sEMG technique is not able to differentiate activities between different suprahyoid muscles, most of the EMG activities recorded from the suprahyoid muscle group originate from the digastric muscle.

In addition to the muscles that control mandibular movements, there are other important muscles involved in food oral transport through controlling the tongue, lips and cheeks. Of this group, the buccinators is a muscle that forms the cheek itself and is more concerned with mastication. The orbicularis oris is a muscle responsible for the closing and protrusion of the lips (compressing, closing, pursing or suction movements). These muscles also appear to be feasible for sEMG studies (Kohyama *et al.*, 2010).

It has also been reported that signals of submental muscles, recorded using bipolar surface electrodes, may reflect tongue movement. One important muscle closely linked to tongue movement could be the anterior belly of the digastric muscle, which was found to be active during all tongue movements (lateral, placement on both the hard palate and the soft palate, and on the floor of the mouth) except retraction (Castro *et al.*, 1999). The recording of such muscles could be extremely useful in investigating the role and functions of the tongue during an eating process, in particular in correlation with the changing textural properties of the food (Kohyama *et al.*, 2010; Shiozawa *et al.*, 1999).

13.3 EMG EXPERIMENTAL DESIGN AND SET-UP

13.3.1 Electrodes, location and placement

Signals recorded from EMG can be noise-like due to temporal and spatial differences among motor units. The intensity or the magnitude of EMG signals not only depends on the potential of muscle motors but is also influenced by a number of other factors (e.g. the skin

impedance, the subcutaneous fat, the size of muscle and the depth of the muscle). The choice of electrodes (size, shape, material, etc.) and the location (placement, orientation, surface cleaning, etc.) are among the most important factors for EMG experimental set-up.

Electrodes are the interface between the muscle and the recording device. Their main function is to convert the biopotentials generated by muscle motors into a current flow. For this reason, the functional properties of electrodes and their close contact with the skin must be considered carefully in order to acquire quality EMG signals. For instance, electrode material plays an important role in the performance of a biopotential measurement system, determining to a great extent the detection limit and the signal-to-noise ratio. Silver–silver chloride (Ag-AgCl) surface electrodes are the most commonly adopted in EMG recordings due to their great stability (noise generated is less than $10\mu\text{V}$) and non-polarisable behaviour (current flowing freely across the interface). Nevertheless, electrodes of other materials such as silver (Ag), gold (Au), nickel (Ni), platinum (Pt), tin (Sn) and stainless steel have also been used for EMG recordings (Cram and Kasman, 1998; Hermens *et al.*, 2000).

The size of the electrode (or the detection surface) should be large enough to be able to record a reasonable pool of motor units but as small as possible to avoid cross-talk. Areas of electrode recording sites are relatively small for chewing muscles because of their short fibres. Therefore, using smaller electrodes for better selectivity and avoiding the pickup of signals from muscles in close proximity is recommended. Furthermore the use of large or thick electrodes can impede the normal chewing behaviour and cause an alteration in the emotional state of the subject (Lapatki *et al.*, 2003). In practice, circular shaped electrodes with diameters between 8 and 10 mm are commonly used for the facial muscles responsible for expression and mastication. These electrodes are normally domed in order to contain an electrolyte paste or gel that provides a bridge between the electrode and the skin but also reduces the effect of electrode slippage and the resulting motion artefact.² The electrode is attached to the skin by double-sided adhesive rings to ensure that a close contact is always maintained between the electrode and the skin.

The configuration in which electrodes are placed is also very important in ensuring the quality of EMG signals. A bipolar array is a typical configuration used in dynamic studies such as mastication. In this configuration two active electrodes and one ground electrode are employed in order to create a differentially amplified system in which signals detected by each electrode with reference to the ground are subtracted from each other. Consequently any signal that is common to both electrodes (normally unwanted noise) will be removed. The difference between the signals therefore gives a true reflection of the activities of the target muscle and will be amplified. This type of configuration can effectively minimise cross-talk.

The ground electrode (also called the reference electrode) provides a common reference to the differential input of the preamplifier. Therefore, the placement of the ground is a critical factor for acquiring a clean EMG signal. It is always preferable to place the ground electrode over a bony prominence, a tissue that is electrically neutral, rather than over a muscle.

It has been established that the optimal location of the electrodes should be between the nearest innervation zone and the farthest tendon of the muscle (Rodrigues-Pedroni *et al.*, 2005). In a bipolar arrangement it is a common practice to place one of the electrodes over the motor point of the muscle but to avoid the motor-end plate region (the terminus of the

²Motion artefacts occur because the electrode slips around the surface of the skin, generating an electrical potential of its own. This can be seen as direct current (DC) shifts and/or massive deflections in the sEMG potentials of the raw EMG signal.

axon at the sarcolemma). The motor point is where the nerve enters the muscle, and it is located on the centre of the belly of the muscle. It is recommended that the second electrode should be placed in line with the first electrode, parallel to muscle fibres and with a 20 mm inter-electrode distance (IED). The centre-to-centre distance between electrodes (Hermens *et al.*, 1999). This distance is a parameter of considerable significance for EMG reproducibility among different subjects and among different trials of the same subject. For different trials the IED must be maintained constantly to ensure that the electrodes are over the same muscle fibres. For jaw-elevator muscles, variations in the spectral and amplitude EMG signals have been observed with even a small electrode displacement of 2.5 mm especially if the detection points are close to the innervation zones or tendons (Castroflorio *et al.*, 2005). For instance, it has been reported that the mean spectral frequency decreases and amplitude increases with an increasing IED (Farina *et al.*, 2002). The use of a small IED has been suggested when single motor points are the object of the study. Conversely, for tests to obtain an overall picture of the muscle responses, a large inter-electrode distance is preferred (Castroflorio *et al.*, 2008).

However, an inter-electrode distance of 20 mm can sometimes be difficult in practice, in particular in the case of facial muscles. Lapatki and collaborators (2003) proposed the use of 4 mm diameter electrodes with an IED of 8 mm in a bipolar array. Such an arrangement makes it possible for a simultaneous observation of multiple muscles in relatively small areas and with much suppressed cross-talk. Large IEDs up to 30 mm are only advisable if such a distance is fixed with the use of special arrays. When two adhesive electrodes with non-fixed distances are applied, significant variability is introduced (Castroflorio *et al.*, 2006).

The placement of electrodes in an optimal position on jaw elevator muscles is in practice a most challenging task. This is because the identification of the region between the innervation zone and tendon is very difficult due to the fact that these muscles have short fibres and shattered innervation zones. Therefore, the use of anatomical landmarks (dominant bone areas, prominences or other structures) is necessary to pinpoint electrode sites and to ensure repeatability of the electrode location.

In surface electromyography, electrode placements can be designated as specific or quasi-specific. A placement is considered to be specific when the muscle to be monitored is close to the surface and is relatively easy to isolate. Temporalis and masseter muscles belong to this category. A placement is quasi-specific when an electrode is placed to record a certain muscle but its proximity to neighbouring muscles makes it difficult to isolate. Action potentials from proximal muscles may appear in the recorded signal due to cross-talk. When dealing with quasi-specific placements two strategies can be considered. One is to choose the correct size of electrode that minimises cross-talk from neighbouring muscles. If reduced electrode size still cannot isolate the target muscle, then it is important to ensure that any contribution from proximal muscles is properly evaluated. The digastric muscle is a good example of this. Its location, small size and close proximity to other suprahyoid muscles make its recording extremely difficult. But luckily other suprahyoid muscles in close proximity to the digastric participate in the same action (mouth opening). In this case the inability to isolate this muscle may not represent a major problem.

Due to facial symmetry, muscle activities can be recorded unilaterally; recording electrodes of a differential amplifier are placed on one side (either right or left) of a homologous muscle, or bilaterally, one electrode is placed on each side (right and left) of a muscle group. Table 13.1 summarises some good practice from recent literature on electrode placement for studies of various facial muscles based on anatomical landmarks, function test and cross-talk. Some terms are explained below.

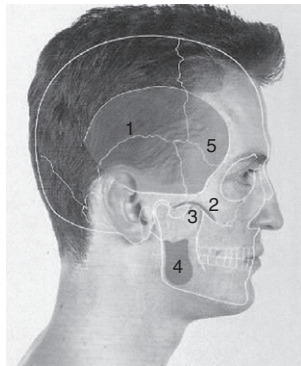
Table 13.1 Electrode location and placement.

Muscles	Electrode site and location according to anatomical landmarks	Muscle function test	Cross-talk
<i>Anterior temporalis</i>	One electrode placed along a line from the corner of the subject's eye to the top of the ear, with the second electrode being placed approximately 1 cm superior to the first in a vertical line (Takada <i>et al.</i>, 1996). The lowest electrode placed just above the zygomatic arch or opposite to the notch of the eye, the second is placed superior to the first and 2 cm apart (Cram and Kasman, 1998).	Palpation of the temple region while subject clenches his/her teeth, lateral deviation of the jaw, protraction and retraction of the jaw, swallowing.	Posterior temporalis, frontalis, corrugator, orbicularis oculi and masseter.
<i>Masseter</i>	Electrodes placed along an imaginary line from the corner of the jaw to the cheek bone and over the belly of the muscle (Cram and Kasman, 1998). One electrode was 10 mm below the camper's plane (a plane extending from the inferior border of the ala of the nose to the superior border of the tragus of the ear) and 20 mm back posterior from the anterior border of the muscle. The second electrode was inferior to the first 20 mm apart and parallel to the longitudinal axis of the muscle fibres (Akagawa and Komiyama, 1992).	Identification of the muscle belly by palpation while asking the subject to clench his/her teeth. A forward head position may affect the resting value of the recordings.	Lateral pterygoid, buccinator and zygomaticus.
<i>Suprahyoid muscles</i>	A pair of electrodes is placed under the chin in the midline, running in the anterior-to-posterior direction (Cram and Kasman, 1998). For unilateral recording of the anterior belly of digastric muscle: drawing an imaginary line which bisects the angle formed by connecting the soft tissue gonion, the soft tissue menton and the midpoint of the hyoid bone. One electrode placed on this line 2 cm away from the soft tissue menton the second positioned after the first on the same line with an inter-electrode distance of 2 cm. For bilateral recording: electrode pair placed with one over each belly (right and left portions) (Green <i>et al.</i>, 1997).	Identification of the muscle by palpation of the area under the chin; asking the subject to swallow a few times, open the jaw or sticking the tip of the tongue to the palate towards the superior front teeth and pressing.	Platysma, sternocleidomastoid.

Table 13.1 (Continued)

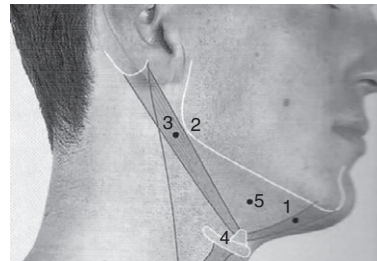
Muscles	Electrode site and location according to anatomical landmarks	Muscle function test	Cross-talk
Buccinator	One electrode placed just lateral to the corner of the mouth, with the second one just lateral to it (Cram and Kasman, 1998).	Ask the subject to press the cheeks against the sides of the teeth and pull corners of lips back as if to play a trumpet.	Masseter, orbicularis oris, risorius, and zygomaticus, depressor.
Inferior orbicularis oris	Electrodes positioned as close as possible to the vermillion border (Lapatki, <i>et al.</i> , 2003).	Ask the subject to contract upper and lower lips (central and peripheral parts).	Adjacent facial muscles.

(a)



1. Posterior temporalis,
- 2,3. Masseter,
4. Superficial masseter,
5. Anterior temporalis.

(b)



1. Anterior belly of digastric muscle,
2. Mandible angle,
3. Posterior belly of digastric muscle,
4. Hyoid bone,
5. Digastric triangle.

Figure 13.4 Recording sites for EMG tests. (a) Anatomical location of closing muscles. (b) Anatomical location of opening muscle. Reproduced and adapted from Lumley, 2008, (figures 2.12 and 3.18), with permission of Elsevier.

- **Anatomical landmarks** To have the precise location of a target muscle requires training and practice. Very useful guides can be gained from the book by Lumley (2008) on clinical examination of visible and palpable anatomy. Examples of anatomical location of closing and opening muscles are shown in Figure 13.4.
- **Muscle function test** The standardisation of electrode position is in practice complicated by the unique facial anatomy of individual subjects. Among individuals there are

differences in morphological characteristics such as: muscle mass, muscle length and adipose tissue. It is therefore critically important that electrodes are adjusted to fit with the subject's anatomy. A muscle function test through visualisation and palpation of the site is essential before electrode placement.

- **Cross-talk** It should be taken into account that electrical potentials from other muscles, even those located further away from the muscle of interest, may also reach the recording site through volume conduction and contribute to the recorded EMG signals, a phenomenon referred to as cross-talk. Cross-talk becomes a major problem when adjacent muscles are coactivated simultaneously with the target muscle. In this case the recorded signal outputs do not correspond to the action under investigation. Strategies such as using proper electrode size, appropriate inter-electrode distance and where possible the exclusion of tasks that activate undesired muscles should be considered to minimise this phenomenon.

13.3.2 Selection criteria of subjects for EMG studies

Apart from experimental factors, foods and participating subjects are the other two major sources of EMG signal variations. Woda and collaborators (2006) classify these into two sets of factors: first extrinsic factors, relating to the properties of the food (e.g. size, geometry, texture, rheological behaviour, moisture content, etc.); and second intrinsic factors, relating to the physiology of individual subjects (e.g. age, gender, dental health, oral physiological conditions, etc.). González *et al.* (2004) also acknowledge that psychological factors (e.g. personality traits and cognitive processes) can cause significant variations in the chewing patterns recorded by EMG. It is therefore recommended that a series of criteria should be examined when selecting subject candidates for EMG studies.

- **Good general health** Good general health of the individual subject is critical for any meaningful EMG study. A brief questionnaire about previous medical history can help to determine whether an individual is a suitable candidate. For some specific studies that have to involve patients, elderly, or other vulnerable populations, a thorough risk assessment has to be conducted.
- **Dental state** Subjects should fulfil the requirement of healthy dental status, including:
 - Full permanent dentition (at least 28 teeth).
 - Free of signs or symptoms of temporo-mandibular dysfunction. Subjects should be checked as to whether they have experienced jaw pain, headache, neck ache, noises in the temporo-mandibular joint, catching or locking of the jaws. In addition, physical evaluation of the subject is also advisable, such as palpation of the joint, jaw, head and neck to identify possible symptoms.
 - Normal occlusion, upper teeth bite slightly ahead of the lowers.
 - No previous orthodontic treatment or orthognathic surgery.
- **Age** Chewing in humans typically emerges between 5 and 8 months old, when teeth start erupting (Sheppard and Mysak, 1984). At around 4 and 5 years of age the neuromuscular activity of chewing becomes well coordinated (Soboļeva *et al.*, 2005). Peyron and collaborators (2004) reported that age was an important factor affecting

EMG activities. They indicated that aging led to lower muscle activity and longer chewing cycles. Therefore, depending on the purpose of a study, subjects from the desired age groups should be selected.

- **Gender** Normally female subjects present lower muscle activity than male subjects, although studies on this matter are few and not very conclusive.
- **Facial morphology** Allometric facial shape can confer a mechanical advantage to particular individuals and can influence chewing patterns. Humans have a great variation in facial forms that can be roughly classified into three different types: relatively long faces (dolichofacial), average faces (mesofacial) and relatively short faces (brachyfacial). Long face subjects normally generate less activity in closing muscles and lower molar biting forces than subjects with medium and short faces. If necessary, cephalometric analysis can be used to extract facial morphological features, such as gonial angle, maxillary height and ramus height (Fogle and Glaros, 1995; Vinyard *et al.*, 2008).
- **Body mass index (BMI)** Muscles contain a large amount of water (~73%) and electrolytes are highly conductive. Anhydrous adipose tissue lying underneath the skin layer is a poor conductor causing significant attenuation of EMG signals. This is why obese individuals tend to have much lower amplitudes than thin individuals (Cram and Kasman, 1998). It is normally assumed that the amount of subcutaneous fat closely correlates with the total body fat. Therefore, to set a certain BMI threshold is advisable for subject selection.

In addition to these criteria, it is also very important to make sure that participants are grouped as either smokers or non-smokers. Participants should also have no particular preference (like or dislike) of the test food and no allergy to the test food and/or food ingredients.

Ethical approval has to be obtained from an appropriate authority prior to EMG testing. Participants who volunteer to take part in tests must be informed in detail about the objectives and procedures of the test and the potential risks involved in experiments. Volunteers should be made aware that they can withdraw from the experiment at any time, without giving any reason and with no negative consequences. A consent form must be signed and filed.

13.3.3 Experimental procedures

An EMG test session consists of the following stages: preparation, set-up, checking and validation, performance and data analysis. Various actions and cautions need to be taken at each stage. These are summarised below.

13.3.3.1 Preparation

- Before the session it is recommended to ask the subject to avoid the consumption of cigarettes and caffeinated beverages, such as, coffee, cola and tea for at least two hours before the test. These foods can contribute to muscle tension.
- Ask the subject to wear appropriate clothes. The wearing of turtle neck shirts or jumpers is particularly unadvisable as they can restrict the access for the proper placement of electrodes over the suprahyoid muscles.

- Ask male subjects to have a clean shave of the areas where electrodes will be placed. Recording of masseter muscles, suprahyoid muscles and orbicularis oris muscles in men with a beard or moustache is impossible and should not be attempted.
- Ask the subject to remove any jewellery, eyeglasses or other metal objects that may interfere with the procedure.

13.3.3.2 *Set-up*

- Locate the sites for the placement of electrodes according to anatomical landmarks. Mark sites and orientation lines, and use a flexible scale band to measure distances (see Table 13.1).
- Perform a muscle function test by palpation for every site to ensure the proper location of the electrode. Do this by asking the subject to perform some specific actions (see Table 13.1).
- Clean the skin to remove dead skin cells by lightly rubbing the area with conductive cleaning pastes or with fine sandpaper (Lapatki *et al.*, 2003), though the use of sandpaper can be annoying and painful. Fridlund and Cacioppo (1986) believe that cleaning with an alcohol swab of rough texture should be sufficient. Carefully rub the skin and let the skin dry before placing electrodes.
- Use double-sided adhesive rings to place the two pickup electrodes and ensure their correct adherence and good contact with the skin. Always position the electrodes oriented parallel to the muscle fibres with a set IED. It is very important that a constant IED is maintained for all the trials within a study.
- Fill the void formed between the electrode and the skin with saline gel or paste ensuring there is no spillage out of the electrodes. Omit this step if pre-gelled electrodes are being used.
- Attach the electrode leads to the amplifier and secure them in such a way that there is enough freedom and space to perform the required actions without lifting the electrode.
- Attach the ground electrode away from the recording site, preferably over bony parts.

13.3.3.3 *Set-up checking and validation*

- Prior to recording, allow electrodes to stabilise for a certain period of time, so that the conductive paste can adequately moisten the skin to minimise the impedance of the electrode–skin interface. Different lengths of stabilisation have been reported, from 5–6 minutes (Celebic *et al.*, 2008), 10–15 minutes (Leung and Hägg, 2001), to 20 minutes (Marras, 1990), depending on the types of instruments and electrodes.
- Test electrode–skin impedance levels with an ohmmeter, ensuring these levels are less than 10 K Ω .
- Connect all the cables to the EMG equipment. All cables must be properly affixed and secured to avoid the pulling of the electrodes or the skin. This issue must be minimised as it can cause discomfort and stress to the subject and interfere with the measurement.
- Ask the subject to sit comfortably in a straight position with their gaze fixed towards a target and refrain from head movements. This is very important to reduce variability due to postural changes.

- Ask the subject to relax and close their mouth in a rest position. A rest posture or habitual mandibular position is achieved when the mandible is maintained in a reasonably constant vertical position with respect to the maxilla, with teeth remaining a few millimetres apart. At rest position, muscles should not show any action potential and EMG amplitudes should be low and close to the noise level (Bérzin, 2004; Castroflorio *et al.*, 2008).
- Start monitoring the muscle activity and check the raw EMG baseline for every target muscle while the subject is relaxed. The EMG signal of a relaxed muscle should be no higher than 10–15 μ V. For a good baseline, the average amplitude could be as low as 3–5 μ V. Recording 30 s of EMG signals to check the baseline is normally recommended. Apart from checking the noise level it is also advisable to ensure a zero offset before recording data and to check possible motion artefacts by visual inspection of any shifts of the baseline.
- Check the validity of EMG signals. This step is very important and indispensable. This is to check that there is actually a presence of EMG activity bursts while performing a specific muscle function test. This test should be performed for every muscle to ensure that the observed EMG signals correspond directly to the muscle action.
- Readjust electrodes if necessary and test again.
- Start the test and perform the desired measurements.

13.3.3.4 Test performance

In order to produce a reliable EMG recording, it is critical to ensure that the subject maintains a natural way of chewing. Some influencing factors are summarised below.

Posture, oral tasks and eye potentials

Apart from chewing, some functional and non-functional oral tasks such as: talking, drinking water, reading aloud, yawning, coughing, jaw play, lip biting, cupping of the hand on the jaw, holding the mandible protruded and laterotruded, some head movements (head yawed, flexion and extension) are normally associated with the activity of the chewing muscles (see Figure 13.5). The reflex of blinking generates some action potentials that could be included in the recording of the anterior temporal muscle. Thus, in order to lessen the effect of such factors in EMG recording, subjects should be asked to keep a comfortable upright position with their gaze fixed towards an eye-level target in front. Speaking, drinking water or leaning must be restrained during recordings.

Chewing style

Mastication in humans is a unilateral process in which a food is positioned between the upper and lower teeth on either the left or the right side, known as the working side. The other side is called the balancing side (Wall and Smith, 2001). However, it is commonly observed that when subjects eat in their habitual manner (free-style), food is continuously passed from one side to another throughout the whole sequence. In some studies subjects were impeded from performing free-style chewing by being asked to manipulate the food on only one side. Brown (1994) found that by doing so subjects needed to concentrate on the way they chewed and that the restriction could cause alteration to their chewing pattern and therefore EMG signals. Mioche and collaborators (1999) observed a lower total muscle activity of the whole chewing sequence for closing muscles (masseter and temporalis) during free-style than during side imposed mastication. They attribute this decrement to the most favourable placement of the food during the opening phase of the masticatory cycle

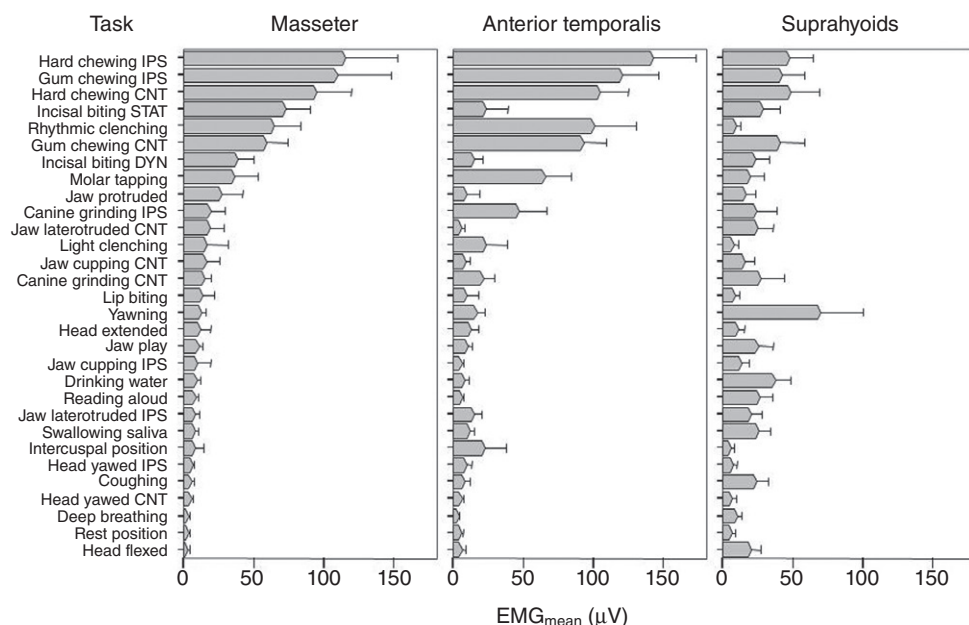


Figure 13.5 Mean amplitude of EMG activity obtained from the masseter, anterior temporalis and suprahyoid muscles during the individual tasks. The length of each column indicates the average ($n = 11$), whereas the error bar indicates the upper 95% confidence limit. Reproduced from Farella *et al.*, 2008, pp.1397–1410, with permission of IOP Publishing Ltd.

facilitating the comminution for the following chew and therefore making the mastication process more efficient. It is desirable that muscle activities of both left and right masseter and temporalis can be measured for eating studies. This, of course, means double numbers of electrodes and the work of data analysis.

Psychological factors

Muscle activation can be triggered by emotions such as anxiety or fear as more energy is sent into the neuromuscular system. This may have an effect on the pattern of movements. The number of chews and the muscle activity before swallowing were found to decrease when subjects were exposed to unpleasant stimuli. It was assumed that subjects focused their attention on the stimuli rather than on the food or that the unpleasant stimuli caused a reduction in the desire to eat and therefore the chewing behaviour (Deiss *et al.*, 2009). Using the first recording session as a mean for subjects to familiarise themselves with the experimental environment has been suggested. It was found that the psychological effects were greatest in the first session as subjects are confronted with an impending and unknown experimental context that can make them stressed and therefore alter their chewing behaviour (Foster *et al.*, 2006; Lassauzay *et al.*, 2000).

Fatigue effect

The fatigue of muscles is a physiological and biochemical process as a result of an intensive activity. Muscle fatigue can lead to increased EMG amplitude due to the recruitment of

more motor units. Chewing muscles, however, are relatively resistant to fatigue. The masseter muscle may contribute to the superior fatigue resistance of jaw closing muscles, presumably due to its significant mitochondrial content. However, fatigue has been observed after subjects chew gum continuously for about 18 minutes at a rate of 80 cycles per minute. But, jaw muscles of healthy subjects normally recover quickly after prolonged chewing of gum (Farella *et al.*, 2001; Mendonça *et al.*, 2005). Different numbers of food samples have been used in various studies. In none of these studies were muscle or intellectual fatigue reported, even when a significant number of repetitions were performed with a considerably large number of samples per session. Nevertheless it is recommended that subjects are allowed to have sporadic breaks along the session to rest, speak or drink, and to move in a manner that they must refrain from during recording.

Food

Shape, size, textural properties and dietary variation are factors that influence jaw-muscle activities. The size of the food, normally expressed in volume, is a factor that determines the aperture of the mouth for biting and the amount of prolonged pressure when biting the food. Also, size can influence the length of time of chewing; smaller pieces normally require less chewing while more chewing is required for large pieces. The shape also affects the ease with which a food can be placed and be manipulated inside the oral cavity.

Food texture is a complex stimulus because it embraces different textural properties such as: hardness, stickiness, cohesiveness, crispiness, crunchiness, chewiness, firmness, elasticity, plasticity and so on. Textural properties are key factors influencing chewing behaviour and the main concern of many EMG studies. During a mastication process, sensations generated by textural attributes are elicited in the mouth and conveyed to the brain stem through oral sensory receptors (see Chapter 2). The sensory feedback therefore generates the next corresponding inputs (physical actions) to be taken on the food. Thus, chewing behaviour has the ability to adapt to changes in texture through mastication.

Natural foods are heterogeneous stimuli. This makes the analysis of motor responses more difficult (Peyron *et al.*, 2002). The adaptation process to food texture has been shown to be constant intra-individually when controlled settings and constant food stimuli were used, but were highly variable between individuals. To overcome this problem, artificial test foods have been used in eating behaviour studies. The main advantage of artificial foods is the provision of samples that have controllable textural properties and geometry. However the disadvantage is that they cannot be swallowed, which means that only part of eating process can be monitored (Foster *et al.*, 2006).

The diet

Diet has been shown to influence the capacities of jaw muscles. Studies in animals show that long term alteration in the pattern of muscle use can be caused by intake of a soft diet. Jaw muscles adapt morphologically and functionally to low masticatory effort for soft foods. Such adaptation is reflected in the reductions in their muscle activity, force output, fibre cross-sectional area and percentage of slow fibres (Grünheid *et al.*, 2009). A study on humans showed that four weeks training with a hard chewing gum seemed to influence the functional capacity of masticatory muscles and increase their strength (Kiliaridis *et al.*, 1995).

Training

Subject training is another important factor for EMG studies. Studies found that trained panellists in sensory assessment exhibit a more constant chewing pattern than untrained

subjects across the samples and sessions. For some reason, trained panellists were found to exert more chewing work over the chewing sequence and to have longer chewing times than untrained panellists (González *et al.*, 1998).

13.4 DATA ANALYSIS

13.4.1 Processing of raw EMG signals

The raw electrical signals obtained from monitoring oral mastication are of the type displayed in Figure 13.6A, normally known as raw EMG signals plotted on a two dimensional diagram of voltage (measured in microvolts, μV) against time (measured in seconds, s). The raw EMG signal presents the amplified potential difference detected at the electrode recording site. The plot can be seen as a representation of the chewing pattern for the comminution of a food. The graph begins with a low amplitude baseline that indicates the rest position of the mandible. When the muscle contracts to perform a chew, there is a burst of

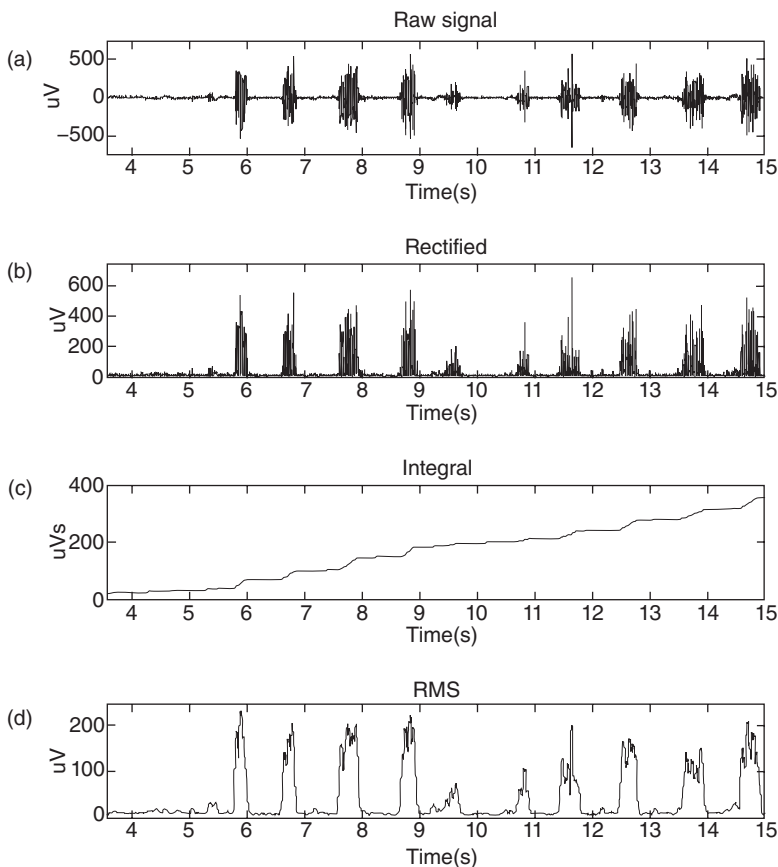


Figure 13.6 Graphical representations of the recorded EMG signals and data processing. (a) Raw EMG signals (unprocessed signal). (b) Rectified signals (full wave rectification). (c) Integration of rectified EMG signal. (d) Root mean square (RMS).

electric signals with suddenly increased amplitude. The signal quickly returns to its baseline once the muscle ceases activation (occlusal stage of a chewing cycle). The EMG amplitude has a close correlation with the magnitude of the biting force, a fact suggesting that an increase in neuronal activity will result in more muscle fibres being recruited and consequently a stronger muscle contraction. Because of the rhythmic and cyclical nature of a mastication process, the EMG signals of an eating process are usually a sequence of electrical bursts with each set of bursts corresponding to one chewing action (or chewing cycle). Such a pattern would normally continue until the food bolus achieves a consistency suitable for swallowing.

The raw EMG signals are very spiky and bipolar in nature. This makes it difficult for interpretation or numerical analysis. For instance, if the amplitude is to be quantified the average will simply be zero due to the cancellation of positive and negative values. Therefore, raw EMG signals serve more as a qualitative resource than a quantitative value. The number of bursts and their corresponding onset–offset (contraction–rest states) of the muscle can be visualised and counted from this electromyogram. In order to extract more useful information from EMG signals, quantitative analysis of raw data is needed. The most common EMG data analysis includes rectification, integration and the root mean square (RMS) calculation.

13.4.1.1 *Rectification*

Rectification is the conversion of bipolar EMG signals to unipolar form. A rectified EMG signal will exhibit only the positive deflections of the original signal. This can be achieved in two different ways. The less commonly used is called half wave rectification, and one simply removes the EMG signals below the baseline (negative deflections). A full wave rectification is done by transposing the negative portion of the signal to the positive side by taking the absolute values (see Figure 13.6B). This method conserves all the energy detected and is preferred.

13.4.1.2 *Integration*

Computing the integral value of the raw EMG signal will return a zero value due to approximately equal positive and negative excursions. Therefore, integration must be carried out on the full rectified wave across the whole spectrum. A typical integration curve is shown in Figure 13.6C, where the integral expressed in microvolt seconds ($\mu\text{V}\cdot\text{s}$) rises rapidly when there are large bursts of activity and remains little changed when no muscle contraction is taking place. The value of the integral is a measure of the electrical activity within the detecting field of the electrodes, reflecting the overall muscle activity or energy produced by the muscle. Apart from full integration of a rectified EMG curve, partial integration of each individual cycle of bursts can also be performed. This analysis could be of particular interest when investigating the changing behaviour of chewing throughout an eating process when the food changes its textural properties.

13.4.1.3 *Root mean square (RMS)*

The RMS is the square root of the sum of the squares of the amplitude of each EMG burst within a recording window divided by the square root of the number of samples within the interval of interest:

$$A[n] = \left[\frac{1}{L} \sum_{i=n-L+1}^{i=n} S_i^2 \right]^{1/2} \quad (13.1)$$

where $A(n)$ is the RMS of the EMG signal, S_i is the EMG signal at time i , and L corresponds to the smoothing window length or a specific time period (Melaku *et al.*, 2001). The RMS is calculated successively throughout the duration of the raw EMG signals. The time window is an important parameter when computing RMS. The smaller the time window the less smooth the resulting curve will be. However, in order to get a curve that follows the trend of the underlying rectified EMG but without the sharp peaks seen in the original spectrum, it is better to use a moving average in which the time windows overlap instead of discrete sections (Payton and Barlett, 2008). The RMS calculation is a preferred parameter as it gives graphs with waveforms that are easier to analyse than the spiky raw EMG (see Figure 13.6D).

13.4.2 Masticatory parameters: analysis of chewing sequence and individual chewing cycles

The analysis of rectified EMG results can be carried out on the whole chewing sequence, certain sections of the chewing sequence, or a particular chewing action. Various masticatory patterns can be extracted to characterise chewing behaviour.

13.4.2.1 Analysis of the whole chewing sequence

The masticatory sequence is defined as the whole set of oral actions performed from the moment of food ingestion (mouth opening) until the terminal swallowing action, when the food is removed completely from the mouth and the jaw returns to its normal rest position. A whole eating sequence can normally be divided in three phases: ingestion, main chewing sequence, and swallowing and oral clearance.

Ingestion

The ingestion phase can be seen as the transfer of food into the mouth and involves the following actions:

- The opening of the mouth.
- Incision or the biting of food by the front teeth. This action is particularly performed when a suitable portion needs to be bitten off from a large piece of food. Soft foods can also be sheared by incisors.
- Prehension. The food is secured by lips. For example wiping the food from a spoon when eating yoghurt or slurping when eating noodles;
- Transfer of food to between the teeth by the tongue.

Incision or prehension actions do not always occur during an eating sequence as they depend on the food being consumed. For instance, if the food is of a size small enough for oral manoeuvring, then only mouth opening and food transportation to the molar teeth will be involved.

Main chewing sequence

This is the main part of an eating process in which food is comminuted and converted to a swallowable bolus by rhythmic chewing. Solid foods undergo a series of chewing cycles and become softened with the help of saliva. Low viscosity liquids are already in a swallowable form and therefore require minimal processing besides checking. Some acidic, cold or strongly tasting liquids may be held in the mouth for a period of time to allow buffers in saliva to raise pH, to equilibrate to body temperature and to be diluted by saliva, as well as to be fully appreciated for their taste and flavour (Prinz *et al.*, 2006).

Many foods however are neither perfectly solid nor perfectly liquid, existing in a state that is often referred to as 'semi-solid' (or soft solid). Typical examples of this kind of food include gelatine desserts, jellies, ice creams, gum confections, peanut butter, puddings and so on. Some of these foods melt into a mobile fluid once put into the mouth (e.g. gelatine desserts, ice creams). However, many others do not melt and therefore need to be chewed into small lumps for swallowing.

It was suggested that facial muscles may have a limited role when soft semi-solid foods are the focus of study because of little muscle activity and limited mandibular movement. However, it could be very interesting to monitor tongue movement during the consumption of such foods. This is simply because the tongue is involved in moving and transporting food inside the oral cavity. The suprahyoid muscles could be highly active even when the mouth is not in the opening phase, because of their close association with tongue movement. Castro and collaborators (1999) concluded that the anterior belly of the digastric muscle was active in all tongue movements (lateral, placement on both the hard palate and the soft palate, and on the floor of the mouth) except retraction.

Swallow and oral clearance

The oral clearance phase in an EMG spectrum is commonly characterised by the presence of some random and non-rhythmic bursts of muscle activities. But jaw-closing muscles are not very active during this phase (Hiimeae *et al.*, 1996). The duration of clearance is highly dependent on the nature of the food. For instance, a sticky food tends to remain adhered to teeth or palate and a prolonged period of oral clearance will be exhibited with increased activity of opening muscles. Visual identification of swallow actions within an EMG spectrum is possible.

Swallow actions are normally classified as interpose swallows and oral clearance (the terminal swallow). Interpose swallows occur within the main chewing sequence, identified as short pauses within the rhythmical sequence. The interpose swallows normally correspond to the swallowing of the liquid portion and fine particles while the non-swallowable portion of food is retained for further oral processing (Brown, 1994; Okada *et al.*, 2007). These swallows can be preceded or succeeded by chewing cycles and are therefore often misinterpreted as part of main chewing sequence. Oral clearance and the terminal swallow correspond to the final swallowing action, at the end of an eating process. A terminal swallow is preceded by some irregular mandibular movements, known as pre-swallowing cycles (Okada *et al.*, 2007).

Figure 13.7 shows the EMG patterns of elevator and depressor muscles during the eating of three different foods of standardised shape and size (a pectin-based jelly confection, carrot and toffee). The different phases of eating process are clearly distinguishable: *A* represents the rest status before eating, *B* is the phase of ingestion, *C* is the phase of oral clearance and terminal swallow, while the main chewing sequences are seen between phases *B* and *C*.

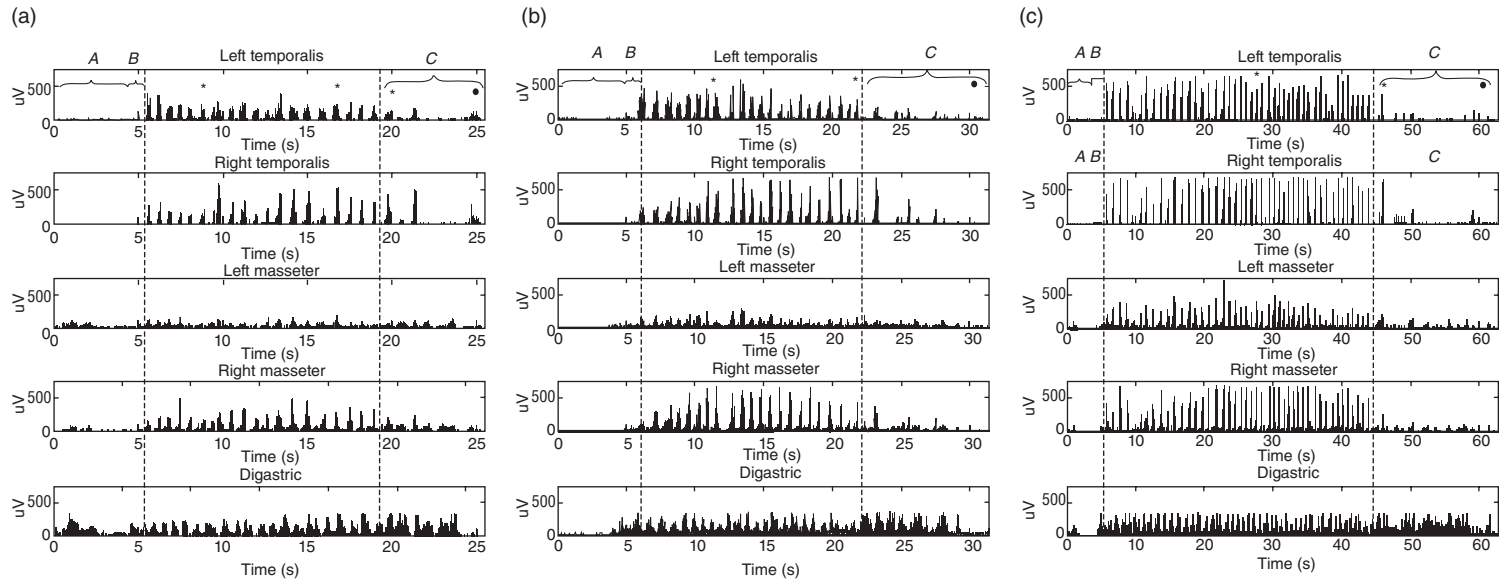


Figure 13.7 Chewing patterns recorded from a female subject while chewing a) jelly confection made from pectin, b) carrot and c) toffee. EMG signals from top to the bottom: left temporalis, right temporalis, left masseter, right masseter and digastric. (a) Period of rest of the muscle (mouth is closed). (b) Ingestion phase (opening of the mouth, activity was observed only in the digastric muscle). (c) Clearance phase (irregular jaw movements or pre-swallowing cycles). The section between dotted lines corresponds to the main chewing sequence (rhythmic chewing movements). *Indicate possible interpose swallowing and • end of oral processing and terminal swallowing action.

Terminology of masticatory EMG parameters has been diverse in literature. Different terms are used even when they refer to parameters of the same physical meaning. Below is a list of parameters most often used in relation to eating and food texture studies.

- **Total sequence duration (s)** This is the total length of time of oral processing of a food material and is considered to be the lapse between the first mouth opening (food ingestion) and the terminal swallowing.
- **Time of main chewing sequence(s)** This is the length of time of an eating process excluding the period of oral clearance (pre-swallowing cycles).
- **Number of chews** This is counted as the number of regular strokes within the main chewing sequence.
- **Muscle activity of a chewing sequence ($\mu V.s$)** Also called the total muscle work or total energy. This is a measure of the electrical activity within the field of the electrodes. It corresponds to the area under the rectified EMG signal and can be evaluated through the integration of the fully rectified signal. This parameter is a measure of the chewing or masticatory effort. Dividing this parameter by the total number of chewing cycles gives the average work per chewing cycle.
- **Time of clearance(s)** This parameter is normally reported as the clearing time. It refers to the time between the end of chewing cycles within the rhythmic chewing sequence and the end of eating process when the mandibular returns to its rest position.
- **Masticatory frequency** This is the rate of chewing and is equal to the number of total chews divided by the time of main chewing sequence.

13.4.2.2 Analysis of individual chewing cycles

A chewing cycle can be divided into two parts: an active period with bursts of muscle activities followed by a resting period. The former consists of numerous EMG bursts and can be identified as a bell-shaped curve within the rectified EMG spectrum. Different masticatory muscles can be out-phased, depending on their association with the oral action. For example, when closing and opening muscles are recorded simultaneously the bursts will appear alternated in time sequence. Burst activities of depressor muscles will be exhibited during the period of jaw opening while the elevator muscles remain at rest, and vice versa. It should be noted that even though the digastric muscle is considered a depressor muscle, it can also be active during jaw closing probably due to tongue movement or restraint of the speed and force of jaw closing (Ferguson, 1999).

Every chewing cycle within the chewing sequence can be divided in two main phases: the preparatory phase and occlusal phase. The preparatory phase can be further divided into two parts: jaw opening and jaw closing. The former consists of the jaw movement for the positioning of the food, involving mainly the activation of depressor muscles while the jaw elevators are relaxed. The latter refers to the period when the jaw elevates until resistance is detected between the teeth. This phase is accomplished by the contraction of the masseter, medial pterygoid and temporalis muscles. The occlusal phase is also called the crushing phase, from the point when the teeth make contact with the food until there is tooth to tooth contact, or until jaw begins to open again. During this phase there is increasing contraction force in all elevator muscles and stimulation of periodontal receptors occurs.

Brown and collaborators (1998) associated specific jaw movements within the trajectory of a chewing cycle to their corresponding segment in EMG signal by coupling kinematic and EMG recordings. They determined that bursts of activity from closing muscles for each

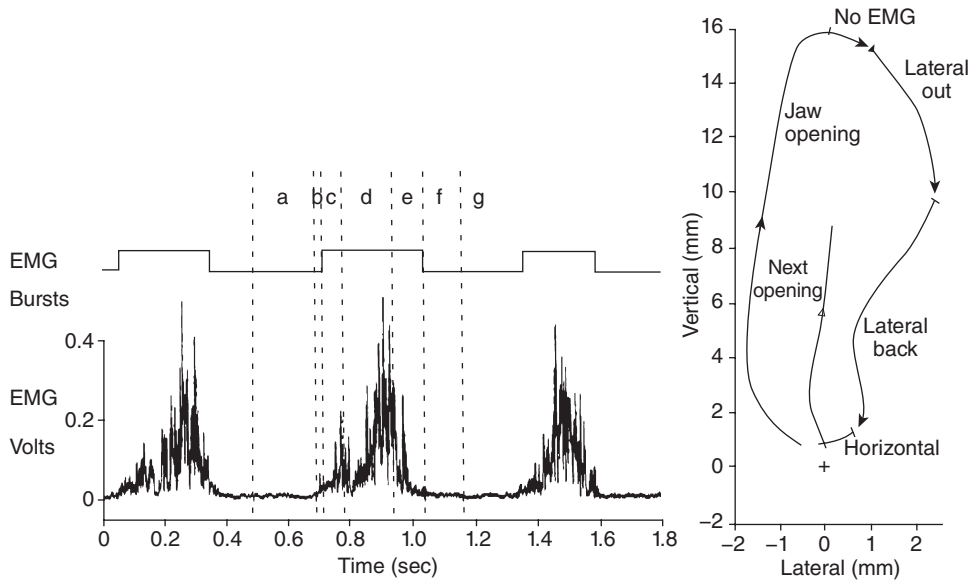


Figure 13.8 The left of the figure shows a recorded EMG of three chews for one subject eating a biscuit. The pooled EMG signal is shown together with identification of the start and end of each stroke. a–g indicate segments of the movement pattern which are reflected in the jaw trajectory shown on the right figure. a = jaw opening, b = start of jaw closing with no associated EMG signal, c = closing movement directed away from the midline (lateral out), d = closing movement directed back towards midline (lateral back), e = horizontal movement associated with EMG signal, f = movement with no associated EMG, g = next opening. Modified from Brown *et al.*, 1998, pp.145–167, with permission of John Wiley & Sons.

chew embrace two parts: one correlated to a vertical closing movement, and a clenching action which includes a degree of horizontal movement (see Figure 13.8). This differentiation is particularly important in analysing the chewing patterns of different foods. It provides some useful information that can be correlated to the texture changes of the food during oral processing.

Due to the excessive amount of data that can be collected from each EMG test, the analysis of all oral actions is not an easy task. Most modern EMG apparatuses provide smart software allowing users easy identification of bursts by moving the cursor across the displayed EMG signals. However, the whole analysis can still be time consuming and involve human error in determining the exact starting and ending point of a chewing cycle. Some studies have reported the use of specific programs or other techniques in combination to identify bursts of activity and to calculate useful masticatory parameters.

In the analysis of an individual chewing cycle, some common masticatory parameters have been used and are listed below (see Figure 13.9 for graphical detail).

- **Muscle onset and offset(s)** The muscle onset corresponds to the time when the burst starts (muscle is being contracted and therefore the amplitude of the EMG signal starts increasing rapidly). Muscle offset refers to the ending of the burst when the muscle ceases its activity and the EMG signal approaches baseline.

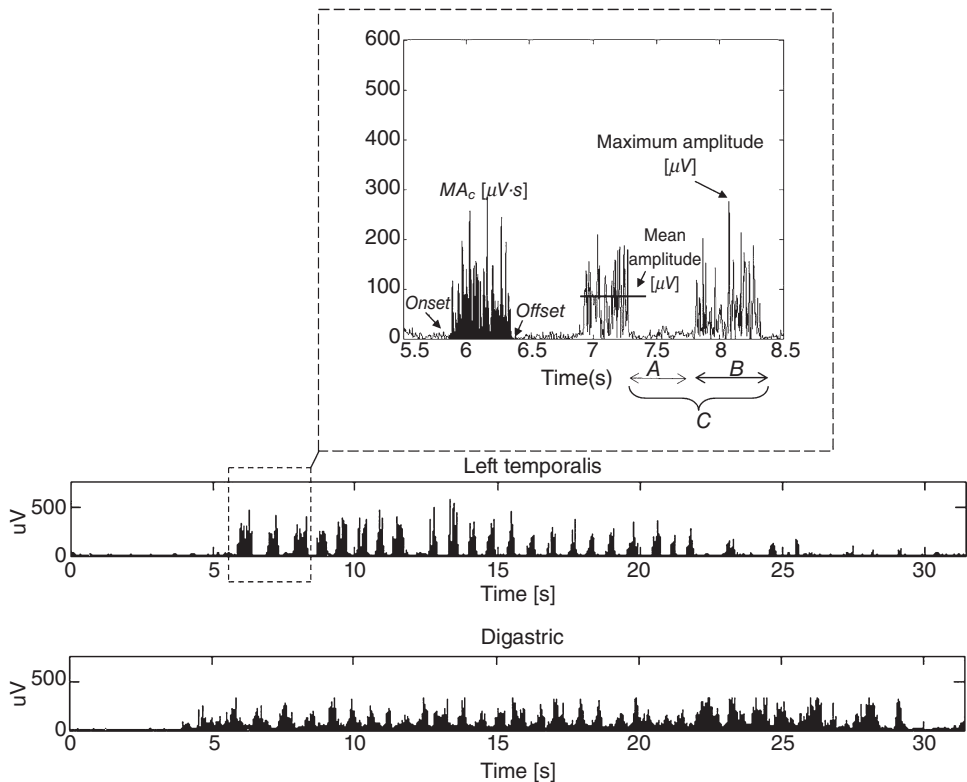


Figure 13.9 Graphical representation of masticatory parameters extracted from a chewing sequence. A: Interburst time. B: Burst duration. C: Chewing cycle time, MA_c : muscle activity per chew (dark area under the curve).

- **Burst duration(s)** The period of time when the muscle is active. It equals to offset time minus the onset time.
- **Interburst time(s)** This refers to the rest period of the muscle when no activity is present. It is the length of time between the end of a cycle and the start of the following one. **Maximum amplitude (μV)** This is the maximum voltage value recorded by the EMG within a chewing cycle (also called peak voltage).
- **Mean amplitude (μV)** Mean value of the voltage of a cycle.
- **Muscle activity of a chewing cycle ($\mu V.s$)** Energy or muscle work applied in each chewing cycle to perform the corresponding muscle actions. This value normally correlates well with the magnitude of the applied force. It corresponds to the area under the curve of each cycle and can be calculated as the integral value between the muscle onset and offset. Sometimes it can be derived as the product of the mean amplitude and duration of the activity burst.
- **Length of chewing cycle (s)** This is the time from the beginning of a cycle to the beginning of the next one.
- **Ascending and descending energy ($\mu V.s$)** The ascending energy corresponds to the area under the ascending curve before the peak of the chewing cycle, while the descending energy corresponds to the area under the descending curve after the peak. Though

the exact meanings of these two parameters are not yet clear, one speculation is that they could be linked respectively to the chewing work for the vertical phase and the chewing work for the horizontal phase.

- **Peak energy ($\mu V.s$)** This is considered the energy over chewing time within a specific segment. It is the product of the maximum voltage (E_p) and peak width at $(\sqrt{2}/2)E_p$. This parameter can be larger or smaller than the total energy of a chewing cycle.

13.5 CASE STUDIES

Since its first application in the 1980s, the EMG technique has been increasingly used for eating studies in relation to food properties, oral physiological conditions and dentistry functions. The technique is extremely useful to reveal oral responses to varied food provisions (e.g. in solid or fluid form, in different geometries, of different size, or of different volume) or to understand oral physiological attributes to food texture appreciation, in particular the studies of food hardness, toughness, stickiness, consistency and so on. Literature reporting such research is abundant. Table 13.2 summarises a few typical studies to highlight different experimental profiles for different applications.

Table 13.2 Literature cases using surface electromyography for the studies of chewing behaviour in relation to food textural properties

Publication Year	Experimental set-up	Masticatory parameters	Main findings
1991, (Diaz-Tay, <i>et al.</i>)	Food of study: roasted peanuts (non-chopped, particle size, median 9.2 mm, range: 6.7–11.2 mm; ground, particles size, median 2.4 mm, range: 2.0–2.8 mm). Subjects: 5 females and 5 males (mean: 19.4 years). Mastication style: Habitual chewing manner. Recorded muscles: left and right anterior temporalis; left and right masseter.	Mean muscle activities; Peak activities; Number of chews; Duration of chews.	● The masseters were more strongly affected than the temporalis. ● The number of chews increased with the increase in both size and weight, but durations were weakly influenced. ● Weight of food affected muscle activity and jaw movement more than the initial size of the food particles.
1999, (Shiozawa <i>et al.</i>)	Food of study: gummi candy (made of gelatine), peanuts, rice cake (5 g gummi candy and rice cake in circular shape*). Subjects: 3 males and 8 females (mean: 30.6 years). Mastication style: habitual chewing side. Recorded muscles: masseter muscle, anterior digastric muscle, mylohyoid muscle.	Chewing time and number of cycles; Chewing rhythm (average); Amplitude of EMG activity; The maximum height of integrated EMG (average).	● Decrease in the amplitude of digastric muscle was due to a reduction in particle size or volume where a wider opening of the mouth was no longer necessary. ● Highly adhesive food required forceful movements of the tongue.

Table 13.2 (Continued)

Publication Year	Experimental set-up	Masticatory parameters	Main findings
1999, (Mioche <i>et al.</i>)	Food of study: canned Frankfurters without the skin, fresh coconut, toffee and French Comté cheese (Cylindrical sample, 1.5 cm diameter, 1.0 cm height). Subjects: 36 (19 males and 17 females, mean: 20 years). Mastication style: free-style, both sides. Recorded muscles: left and right masseter, anterior temporalis.	Chewing time before the final swallow; Averaged duration of a single chew; Maximum and mean voltage of a chewing cycle; Sum of the integrated areas of the sequence; Mean muscle work per chew.	● Total muscle work increased with hardness. ● Longer sequence duration of toffee could be due to its stickiness slowing down the opening phase. ● Muscle work per chew could be the sensory clue used by individual to perceive stress-related variables of food texture.
2000, (Mathoniere <i>et al.</i>)	Food of study: 12 types of beef (1.5 cm cubes, weighing $\approx$ 3.5 g). Subjects: 6 females and 5 males (25 to 50 years). Mastication style: natural chewing. Recorded muscles: left and right temporalis, left and right masseter.	For each cycle: Duration; Mean voltage; Maximum voltage; Muscle work. For the entire sequence: Total muscle work.	● Correlation between elasticity and EMG (first two chews) were not significant. ● Tenderness was significantly correlated with EMG (from the third chew). ● Good correlation between overall tenderness and parameters from the seven chews in the middle of the sequence. ● Juiciness was well correlated with the first two chews variables.
2002, (Carson <i>et al.</i>)	Food of study: 3 types of cakes of same firmness and 6 commercial breads (samples were in 20 $\times$ 20 mm cubes). Subjects: 9 panellists. Mastication style: unilateral chewing (right side on the mouth). Recorded muscles: right masseter.	Total energy; Peak energy; Fourier power (the muscle work intensity obtained from the power spectrum of Fast Fourier Transform); Ascending energy; Descending energy.	● Descending energy could be a suitable parameter for predicting cohesiveness. ● Cohesiveness estimation from EMG extracts produced good correlations ($r \geq 0.80$) with sensory cohesiveness but only useful to distinguish cohesiveness among products with small differences in hardness or other textural properties.
2005, (Kohyama <i>et al.</i>)	Food of study: cooked rice with different amounts of water (a spoonful). Subjects: 10 volunteers (mean age 32.4 years). Mastication style: free-style chewing. Recorded muscles: left and right anterior temporalis, left and right masseter, anterior digastric muscles.	For jaw-closing muscles: Number of chewing strokes; Mastication time; The maximum voltage; Burst duration; Muscle activity. For jaw-opening muscles: The maximum voltage; Bursts duration Muscle activity.	● Jaw-closing activity reflected the firmness of the sample evaluated instrumentally. ● Jaw-opening activity was related to the instrumental adhesiveness of sample. ● Cohesiveness correlated also well with jaw-opening activity and with the adhesiveness of the rice samples tested. However activity of opening muscles were not related to the cohesiveness defined by ISO 11036.

(Continued)

Table 13.2 (Continued)

Publication Year	Experimental set-up	Masticatory parameters	Main findings
2006, (Foster <i>et al.</i>)	Food of study: 4 jellied confectionery (elastic products); 4 caramel confectionery (plastic products) (cylindrical shape, 2 cm diameter and 1 cm height). Subjects: 15 males (24.1 ± 1.9 years). Mastication style: unilateral chewing (preferred side). Recorded muscles: left and right temporalis, left and right masseter.	<i>For the whole sequence:</i> Number of chewing strokes; Masticatory frequency; EMG activity; Mean vertical and lateral amplitudes.³ <i>For individual cycles:</i> EMG activity; Opening, closing and occlusal durations; Vertical and lateral amplitudes; Opening and closing velocities.⁴	● Sequence duration, number of cycles, EMG activity per sequence and EMG activity per cycle increased significantly with hardness regardless the food type. ● Plastic foods were chewed at lower frequencies than elastic products. ● The effect of hardness on masticatory frequency was most important during initial stage of a masticatory sequence. ● Vertical amplitude was affected mostly by the rheological properties of the food.
2010, (Kohyama <i>et al.</i>)	Food of study: buckwheat noodles (a mouthful ~15 g) of: 1) standard buckwheat noodles length, and 2) 3 cm length. Subjects: 8 males and 5 females (24 to 43 years). Mastication style: free-style chewing or slurping. Recorded muscles: left and right masseter, suprahyoid musculature, left side of the inferior orbicularis oris muscles.	<i>For masseter muscles:</i> Number of chewing strokes; Mastication time; Mean chewing cycle time; <i>For orbicularis oris muscles:</i> Number of strokes; Cycle time; <i>For each stroke:</i> Amplitude; Burst duration; Muscle activity; Mastication effort.	● Slurping action required a longer mastication period but smaller EMG amplitude. ● Cutting the noodles short reduced the mastication effort.

13.6 CONCLUDING REMARKS

Surface electromyography is a promising technique for the studies of chewing behaviour in relation to oral physiological conditions and the changing textural properties of food. The technique offers reliable real-time measurements of the activities of facial/oral muscles during an eating process. In order to obtain quality EMG data, experimental works have to be properly planned in detail and in advance, including the choice of electrodes, selection and location of target muscles, and the set up of the surrounding environment. The selection

³Data obtained from recording of jaw movements.

⁴Data obtained from recording of jaw movements.

of participating subjects must follow certain criteria and ethical approval must be obtained beforehand. Data analysis and interpretation can be most time consuming and are still matters for further exploration. A number of parameters can be extracted from EMG signals either for the whole eating sequence or for an individual chewing cycle, or even for some particular oral actions (such as mouth opening and closing, tongue movements, swallowing, oral clearing, etc). These parameters can give both qualitative and quantitative characterisation of oral behaviour in response to the specific textural properties of a food.

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14 Soft Machine Mechanics and Oral Texture Perception

Micha Peleg and Maria G. Corradini

14.1 INTRODUCTION

Eating is a physiological necessity and for the large majority of humans a pleasurable activity. For a food to be palatable it has to look attractive, taste good and have a desirable texture. There is no universal agreement on what makes a food agreeable, appetising or delicious, or on the contrary, objectionable, unappetising or inedible. The criteria can vary dramatically between individuals and cultures. Even the same person can develop an affection to an erstwhile objectionable food or a dislike to a previously favourite one. Yet, if we ignore preparation, the way people actually eat food is remarkably similar. This suggests that eating involves two mutually dependent domains. In one, physical and chemical stimuli are generated and trigger a physiological response, and in the other the neurological activity that accompanies these processes is transmitted to the brain through the nervous system to create sensory perception of the food's organoleptic properties.

With this simplistic view in mind, one can attempt to deal with the operation of the tactile sensory system as if it were a testing machine and assign the sensory and perception components to its sensors, control system and data processing software. The analogy is far from perfect, of course. The mouth or even the fingers bear little resemblance to manmade mechanical instruments. Yet, the function of both is regulated by the same mechanical principles that determine their sensitivity and dictate their output's characteristics.

A comprehensive theory of oral texture perception would have to be based on the fundamentals of very different scientific disciplines from physiology, anatomy and neurology to physics (especially mechanics, rheology and acoustics), informatics, cognition and semantics. Each field can shed light on different aspects of the process whereby a stimulus, or rather an ensemble of stimuli, which is generated during food manipulation in the mouth, is sensed by receptors and coded into series of electrical pulses. These are passed to the brain through the nervous system where they are translated into perceived textural attributes, which humans can describe in words and assess quantitatively using absolute or relative intensity scales. Not all the process's fundamentals, let alone the details, are fully understood. They are being intensively studied in the most prestigious neuroscience and neurobiology laboratories of the world, albeit rarely in the context of food texture perception by

humans. Many studies of food texture, especially the early ones, have been motivated by the food and agricultural industries' needs. Thus, their primary goal was frequently to determine the optimal ripeness of fruits and vegetables for harvest. The instruments and methods have later been adapted to replace humans as a tool to assess the texture in food product development and in quality control. Instrumental methods have also been amply used in studies of the structure-texture relationship as the basis of novel food development. Many studies have focused on the *correlation* between mechanical or rheological properties, measured with a testing machine or viscometer, and the rating or ranking of textural properties by trained and untrained sensory panels. In these studies, much emphasis has been put on the *statistical* design of the test and interpretation of its results. There is a large and growing body of literature on these subjects, which in recent years has been expanded and now includes reports on *in situ* measurements of forces and motions during mastication. These, will reveal how texture is actually sensed by humans, which is a key to understanding how it is perceived.

This chapter has two narrow objectives. One is to highlight how the mechanical properties of the sensory system itself, those of the jaws, teeth and tongue in particular, might affect the generation of stimuli during textural evaluation of foods. The other is to identify some of the theoretical limitations of quantifying the perceived 'texture' or 'textural attributes' of foods. Most of the discussion will focus on the purely mechanical stimuli that the oral system generates, senses and processes, and how they compare with what a rigid, manmade testing machine records. The chapter is primarily a statement of opinion. It is almost exclusively based on theoretical considerations rather than on collected experimental sensory data or actual measurements of stresses, strains and rates in the mouth. Admittedly, many of our assumptions are speculative and their validity is yet to be confirmed experimentally. However, we believe that even in their simplistic form the presented analyses shed light on an important aspect of the tactile system operation that has been largely ignored in texture studies. We also believe that the analyses' results, despite being abstract and general, can explain certain observed patterns in texture assessment that might have practical applications in food product development and quality assurance. We are convinced that understanding the potential role of the jaw's and tongue's own mechanical properties in texture perception could advance the field of texture studies and might find practical applications not only in food but in other fields too. The same can be said about the analysis of the sensory system's sensitivity as a testing machine. Some readers would consider our approach over simplistic, and for a good reason. There is no doubt that the physiological, neurological, geometrical and histological aspects, which are barely mentioned in the discussion, play a significant and most likely crucial part in the sensation process. But we still believe that certain basic physical principles apply *regardless* of the details and therefore ought to be considered and examined first. To highlight the point, consider the following. When trying to correlate a manmade machine's mechanical parameters with human sensory evaluations, one of the first questions to be asked should be whether the machine and the humans have the same sensitivity to these attributes and if not which is more sensitive. However, this seemingly obvious issue has rarely been explicitly addressed in the vast literature on the texture of foods. Other, not unrelated, questions are whether the scatter in mechanical measurements in solid foods is due to textural non-homogeneity and whether the scatter in sensory evaluations is due to inherent differences in the sensation mode among individual humans. Or maybe both play a role, in which case how could the non-uniformity and mode of perception be separated? Such questions need qualitative answers since they

are not merely a statistical issue. Other aspects, notably the mastication and testing rates, have received more attention. However, most mechanical testing machines operate at much lower displacement rates than those that are generated in the mouth. A pertinent question, therefore, is whether there are foods whose viscoelastic properties are such that the machine can reveal them but not the mouth, or the other way around, that they can be sensed by the mouth but not by the testing instrument—see Peleg and Campanella (1989) and below. This rate issue is of course further complicated by the fact that during mastication the food specimen continuously changes size and geometry, not to mention its infusion with saliva. In foods such as ice cream and chocolate, melting and heat transfer related effects might be overwhelming. Thus an attempt to correlate the output of manmade testing machines and the sensory response of humans in such cases will create a particular challenge to a food texture researcher. Still, and despite all the above and additional complications not mentioned, both the mechanical testing instrument and the sensory system have to abide by physical constraints that apply to *all* testing machines. These, as already stated, are the focus of this chapter.

14.2 SENSORY TERMS AND VOCABULARY

Terminology has been the central topic of many publications on texture, and much emphasis has been placed on the ‘definition’ of textural attributes. Nevertheless, there is still no universal agreement on the wording, how a particular attribute is sensed and/or under what conditions it can be measured instrumentally. The disagreement or incongruity of the textural terms is not surprising. A case in point is that the classification of textural properties can be different in different languages. Much of the confusion stems from basic semantics. By assigning a word or term we carve a multidimensional continuous reality into discrete or linear categories that need not even exist. A good example is the ‘heaviness’ of cream (referring to its consistency), which has an *inverse relation* to its density (Peleg, 1983a,b). Another is the arbitrary division of the ‘hard–soft’ domain into ‘hard–firm–soft’. Can anyone tell where the transition from ‘hard’ to ‘firm’ or ‘firm’ to ‘soft’ occurs? Words have connotations and multi-dimensional meaning, which rarely, if ever, fully overlap. The result is that ‘creamy’ can be associated with smoothness (primarily determined by particle size) and hence be the opposite of ‘grainy’, but also ‘viscous’ in contrast with ‘watery’, say.

The semantic problems with many sensory terms are far from being resolved. Because of different connotations, ‘sensory scales’ based on different foods should always be treated with extreme caution. There is simply no way around the fact that the ‘hardness’ of a biscuit, say, is not the same as the ‘hardness’ of boiled egg (let alone of a ‘hard exam’, ‘hard radiation’ or ‘hard water’ in which the term has nothing to do with mechanical strength). Therefore the ‘hardness’ data derived from different foods should not be connected if plotted on the same graph. One should also remember that the sensory response intensity to different mechanical attributes within a group (biscuits and boiled eggs in the above example) need not be the same as would be inferred from a plot where they are displayed together as shown in Figure 14.1 (after Peleg, 1983a,b, 2006). Apart from the semantic issue, the comparison of different foods using the same adjective can also be influenced by non-mechanical stimuli, acoustic and thermal for example, and be affected by different sensitivities (see below).

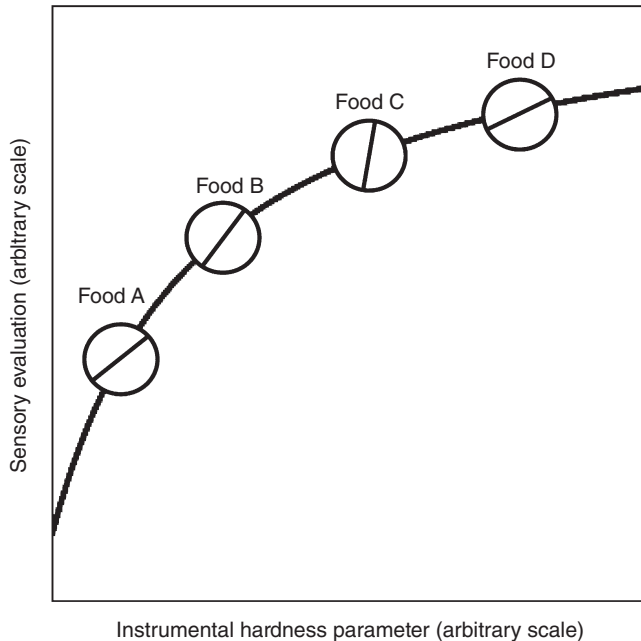


Figure 14.1 A hypothetical 'correlation' between sensory and mechanical 'hardness' determined in the same food or from different foods. Notice that a trend revealed by the latter might be inapplicable to the former. After Peleg (1983a, b, 2006).

14.3 SOFT MACHINE MECHANICS

The tongue is a soft compressible tissue, relative to many, perhaps most, solid foods. The jaw–teeth system is much stiffer (or more rigid) in comparison, but still not as stiff as most mechanical testing machines used in engineering. Both the tongue and jaws are moved by muscles, which have mechanoreceptors imbedded in them. Their combined response, which varies during mastication, is most probably what produces the sensation of a solid food's 'texture'. Interpretation of this response has at least three main aspects:

- 1 The effect of the tongue and jaw's own rheological properties on the magnitude of the generated 'stimulus' and how it varies with time. The same can be said of the mechanoreceptors themselves, which are also made of soft biological materials.
- 2 The effect of the tissues' and receptors' rheological properties on the sensory system's *mechanical sensitivity*, and how it varies with time during mastication.
- 3 The sensory system's performance as an 'amplifier', playing a role equivalent to that of a manmade mechanical testing machine's electronic system.

14.3.1 The signal generated by stiff and soft machines

A schematic view of a soft and a perfectly rigid machine is given in Figure 14.2. The figure shows that in a rigid machine, the overall mechanical resistance of machine-specimen array is for all practical purposes that of the specimen. The overall mechanical resistance of a

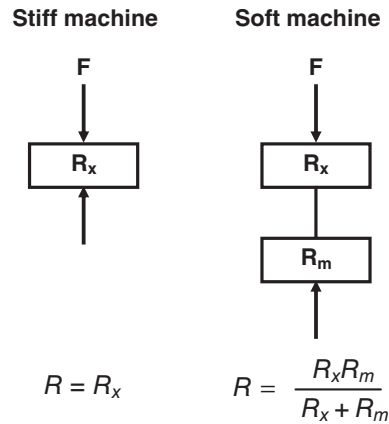


Figure 14.2 Soft and rigid mechanical testing machines. R_m , R_x and R are the mechanical resistances of the machine, tested specimen and their in series array, respectively.

'soft machine' is determined by the combined resistances of the specimen *and* of the machine, and in the extreme by that of the *machine only*. Thus, the whole force–time relationship generated by a rigid mechanical testing machine, that is 'the stimulus equivalent', must be different from that generated by a soft machine. Moreover, the tongue and tissues that surround the teeth's roots, gums and cheeks all have viscoelastic and/or viscoplastic properties. These affect both the mechanical resistance of the array, and its response to the deformation rate and how it varies with time. As already stated, the same can be said about the mechanoreceptors themselves, which are also made of organic components. This means that the generated and perceived mechanical stimulus is not only solely a response to the rheological properties of the sensed food but also to the simultaneous changes that occur in the sensory system itself. Campanella and Peleg (1988, 1989) studied the potential role of the tissues' own viscoelasticity in the mechanical stimulus generation with the aid of simple rheological models based on mechanical analogues. They showed that the rheological properties of the combined food-sensory system could be very different from that of either the food or the sensory system alone. To demonstrate the point, consider an ideal elastic specimen subjected to a rigid and soft viscoelastic machine as shown in Figure 14.3. In the rigid machine, the output will be rate independent, and at constant displacement the signal will remain constant. In contrast, the soft machine's output when testing the same object will be displacement-rate dependent, and at a constant displacement, the signal will relax as a result of the *tissue's* viscoelasticity. (In the array shown in the figure the force will approach, asymptotically, a finite residual level.) The same kind of behaviour will be exhibited in a creep test. Under a constant load (actually stress), the displacement in the stiff machine would remain constant but in a soft viscoelastic machine it will rise continually as demonstrated in the figure (bottom). The actual geometry in the mouth, the rheological properties of the tissues and receptors involved, as well as those of a masticated food, are obviously more complicated than is shown in the figure. Yet the physical principles that govern their mechanics are the same. In addition, the mechanical signal's relaxation is also caused by the mechanoreceptors' 'adaptation', an issue to which we'll return when dealing with their performance playing the role of the sensory system's 'amplifier'.

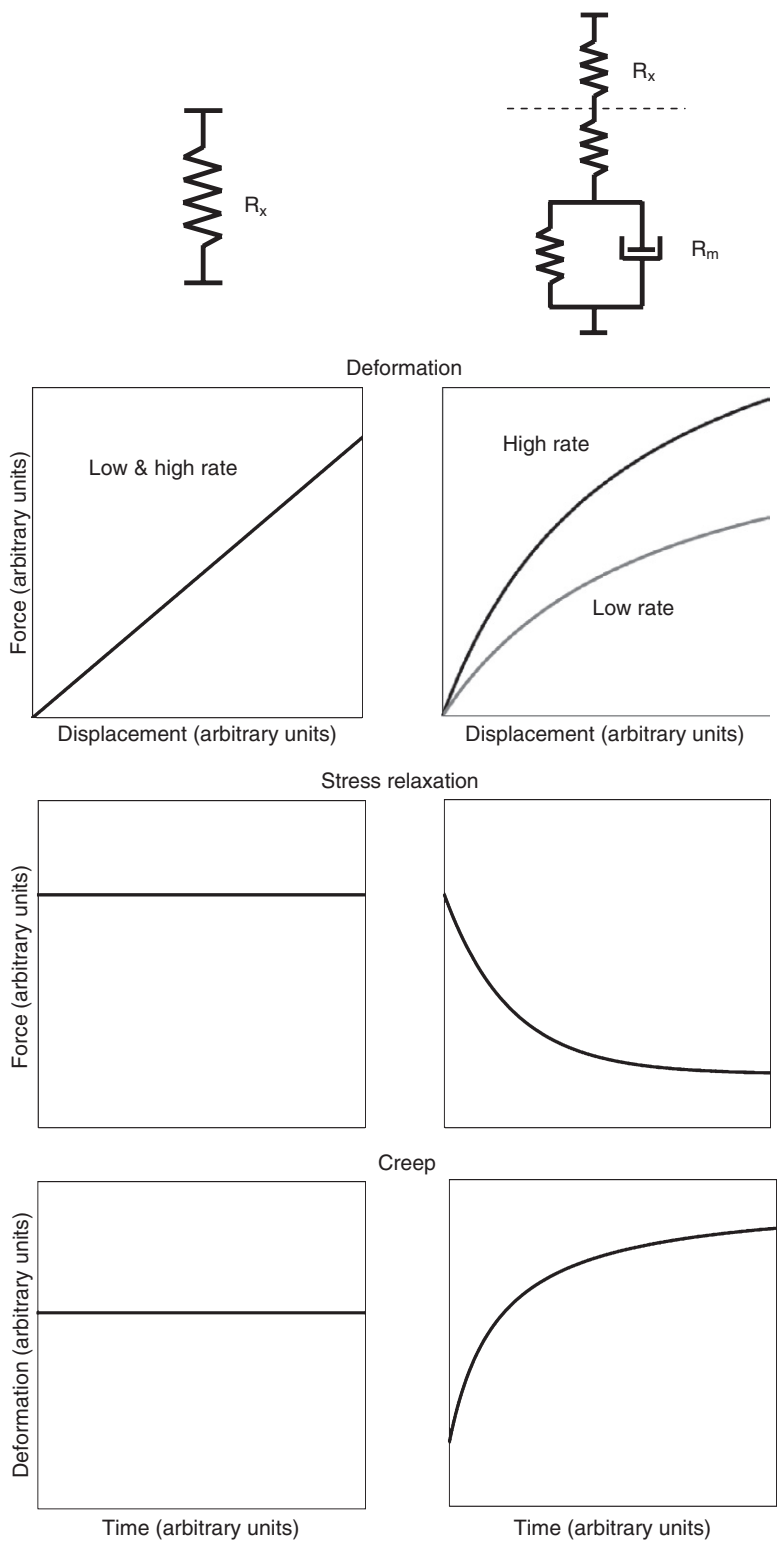


Figure 14.3 Demonstration of how the viscoelastic properties of a soft machine can affect its output in testing an ideal elastic specimen.

14.3.2 Mechanical sensitivity of soft machines

A manmade machines' frame, as already stated, is deliberately built of rigid metals and so is its sensor, be it a load cells assembly, or, in 'cruder' testing machines, the beam in which a LVDT (Linear Variable Differential Transformer) is imbedded. The rigid construction guarantees that the deformation in the machine and sensor array will always be negligible relative to that imposed on the specimen, when the machine operates at its designed load range. 'Mechanical sensitivity' can be defined in more than one way (Peleg and Campanella, 1989). Suppose that the specimen's mechanical resistance is R_x and that of the machine's R_m as shown in Figure 14.2. Since the two resistances are in series as demonstrated in the previous section, the total resistance of the array is:

$$R = \frac{R_m R_x}{R_m + R_x} \quad (14.1)$$

Thus if $R_m \gg R_x$, $R \approx R_x$, that is the overall mechanical resistance of the array is practically the same as that of the tested specimen. Or conversely, if $R_m \ll R_x$ (as when we press a metal object between our fingers – see below) then $R \approx R_m$.

The system's mechanical sensitivity, S_m , can be defined as the output to input ratio, R/R_x in which case it will be:

$$S_m = \frac{R_m}{R_m + R_x} \quad (14.2)$$

or

$$S_m = \frac{1}{1 + \frac{R_x}{R_m}} \quad (14.2a)$$

Notice that when $R_m \gg R_x$, as in rigid manmade mechanical testing machines, $S_m \approx 1$, that is the machine's output is proportional to the input. The other extreme is when $R_m \ll R_x$, that is, the specimen is much stiffer than the machine as would be the case if we attempted to deform a hard candy, or (accidentally) a stone, between two teeth. In this case, according to Equation 14.2, the system's mechanical sensitivity will be practically zero, that is $S_m \approx 0$. In between, when R_m and R_x are of comparable magnitude, the S_m vs. R_x relationships will have the shape shown in Figure 14.4.

A machine's mechanical sensitivity can also be defined as the output's *rate of change* with respect to the input, that is $S_m = dR/dR_x$ (Peleg and Campanella, 1989). In this case the relationship between S_m and R_x/R_m would be:

$$S_m = \frac{R_m^2}{(R_m + R_x)^2} \quad (14.3)$$

Here again, when $R_m \gg R_x$, $S_m \approx 1$ and when $R_m \ll R_x$, $S_m \approx 0$.

Equations 14.1, 14.2 and 14.3 are only valid for systems where the geometry does not change and both R_x and R_m remain constant throughout the test. Obviously, this is not the

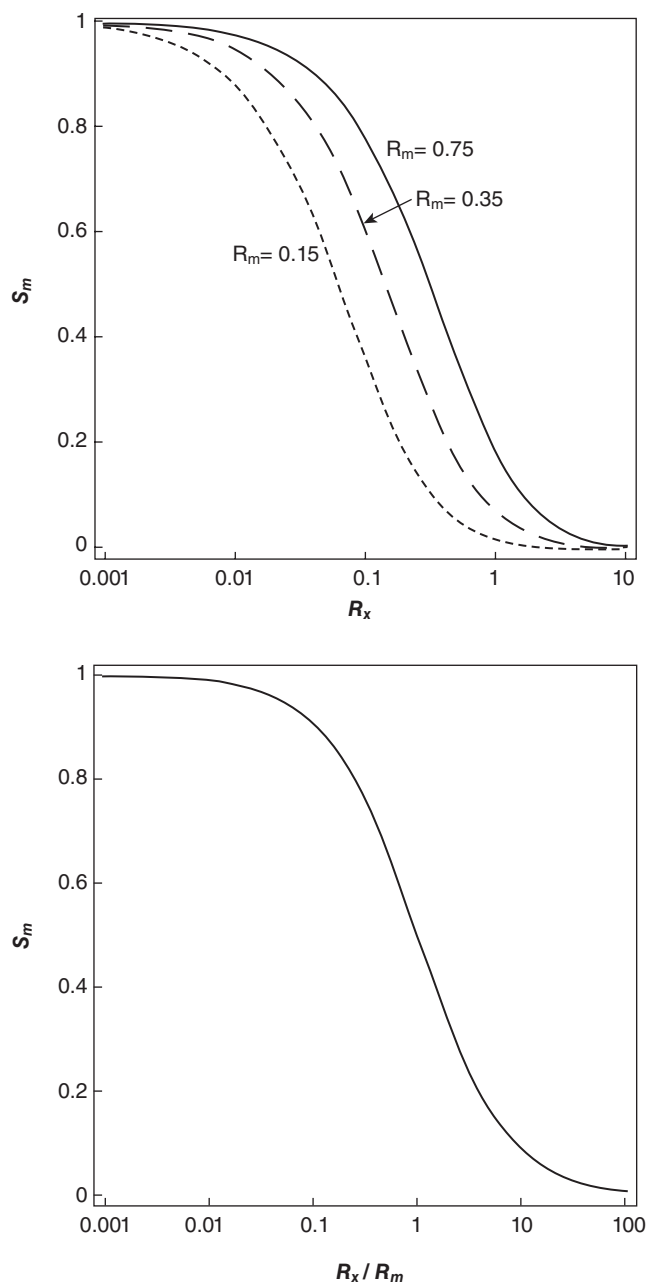


Figure 14.4 The mechanical sensitivity of a testing system as a function of the ratio between the mechanical resistances of the tested specimen, R_x , and that of the machine, R_m , calculated with Equation 14.2a. After Peleg (1980) and Peleg and Campanella (1989).

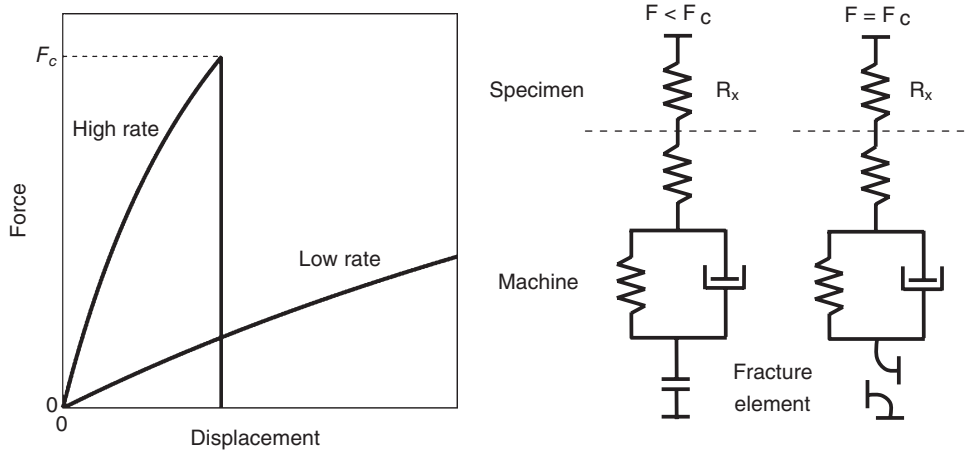


Figure 14.5 A model of how the rate might determine whether a tooth will be cracked in an attempt to break a hard object. After Peleg and Normand (1982).

case in the mouth. During mastication, a specimen's morphology and properties continuously change, tissues may be compressed and so therefore some of the receptors. Yet, the plots shown in Figure 14.4 are still very pertinent, at least for the extreme cases, that is where $R_m \gg R_x$ or $R_m \ll R_x$ in which case the geometric and other details are less important. The implication is that while the tongue can be a very sensitive instrument for very soft foods (or foods moistened by saliva), it has no discriminatory power when it comes to hard (i.e., stiff) foods, a topic to which we will return. The same is most probably true for the jaw and teeth system when it comes to trying to break a hard candy or crack a nut, say, that is it would be difficult if not totally impossible for a person to assess *differences* in the stiffness of such objects. Notice that when $R_x \gg R_m$, as in the above example, the attempt might result in a broken tooth or teeth. This usually does not happen because we adjust the deformation rate to avoid it. The situation is described schematically in Figure 14.5 where the jaw/tooth is described by a mechanical analogue having a fracture element in series (Peleg, 1983a,b). At low deformation rates, the 'viscous' element of the system complies and the force that develops in the array remains low as shown in the figure. Thus when we try to crack a nut with the teeth we do it very slowly. In contrast, at the normal high rates of mastication, an unnoticed nutshell fragment or a little piece of stone in the food can crack a tooth. The validity of the model shown in Figure 14.5, and that of the explanation that it provides, are yet to be confirmed. Nevertheless, that there is a limit not only to the sensory system's mechanical sensitivity but also to its mechanical integrity is beyond doubt (see below).

14.4 THE 'AMPLIFIER' AND SENSORY SENSITIVITY

Anyone who has ever had a tooth cavity and felt it with their tongue must realise that size is perceived as much larger than it looks when seen in a mirror. This 'sensory amplification' is probably the result of the tongue's richness in mechanoreceptors and nerve endings. Moreover, in 'exploring' the cavity, the tongue demonstrates its capacity to *locate* objects in the mouth and sense their morphology rather than to assess their mechanical properties.

Relatively, the gums and cheeks are less endowed with receptors and nerve endings, although they too can feel an object. Moreover, the tongue can sense the gums and cheeks while they 'feel' the tongue at the same time. Manmade machines have nothing similar in their construction. In reality, the issue of mechanical sensitivity would be more complicated even if we could ignore the roles of changing geometry, saliva secretion and other factors. Even in perfect test geometry, the tongue's *compressibility* would produce unexpected effects, at least theoretically. Recall that the mechanical sensitivity, S_m , regardless of how it is defined, primarily depends on the relationship between R_x and R_m . This relation changes with time, of course, as the food is broken and wetted. But it also changes if the tongue compresses, which makes it stiffer. In other words, R_m in our system can increase during the 'test'. At the same time, the specimen's mechanical resistance, R_x , can remain practically unchanged at best, as in chewed chewing gum, but most probably it will decrease. When the machine's and specimen's resistances are both continuously changing there are several possibilities, some of which are shown schematically in Figure 14.6. Notice that they even include a region of *negative sensitivity* (Peleg and Campanella, 1989). This might occur if the specimen compresses faster than the tongue, as could be the situation with cream cheese, at least theoretically.

One should also remember that the force exerted by a compressed flat specimen is considerably reduced if the contact surfaces are *lubricated*. Theoretically, this would happen in both Newtonian and non-Newtonian liquids, that is in a squeezing flow of polymers (Soskey and Winter, 1985) and in foods (Campanella and Peleg, 2002). The same can and has been observed in flat rubbery materials (Gent and Lindlay, 1959) and also in foods, for example Chu and Peleg (1985). There are very few reports in the rheology and texture literatures on the effect of the tongue's own deformability and lubrication and on the mouth's performance as a mechanical testing instrument (Lee and Peleg, 1990). The same can be said about the tongue's mechanical sensitivity, which is probably still largely unknown. For these reasons, application of the 'amplifier' analogy to oral perception of texture should be treated with caution. What we can say with a certain degree of confidence is that unlike in a stiff manmade machine operating at its designed load range, the sensory sensitivity in the mouth need not be constant in time, regardless of how it is defined.

Most published relations between stimulus and its perceived intensity suggest that there is a power-law relation between them, an observation known as Weber or Weber–Fechner law, and in another form as Stevens law. Thus, when plotted on semi-logarithmic or logarithmic coordinates, the relationship between the sensory response and stimulus intensity is frequently a straight line whose slope, n , varies according to the stimulus kind. The magnitude of n is usually between about 0.4 (for viscosity) to 2 (for 'tactual roughness') (Friedman *et al.*, 2008; Harpers and Stevens, 1964; Moskowitz, 1977; Stevens, 1975). Obviously, the perceived stimulus intensity cannot rise indefinitely as the above mathematical logarithmic relationships imply. Thus the perceived intensity versus the objective stimulus intensity relationship over the entire range is most likely sigmoid (Campanella and Peleg, 1988), starting at zero response at the sensation's threshold and ending with a flat region indicating saturation. Or, if the stimulus exceeds a certain level, the response might increase sharply ending in pain. It is not uncommon for a sigmoid relationship to have *regions* that can be described as power-law relationships. However, the slope, or power n , will be different if this region is in the centre, close to the sensation's threshold or to the system's saturation. Let us therefore consider that the response intensity, I_s , of a sensory system to a mechanical stimulus, R_x , can be characterised by a sigmoid curve as shown in Figure 14.7 and described mathematically by a logistic model of the kind:

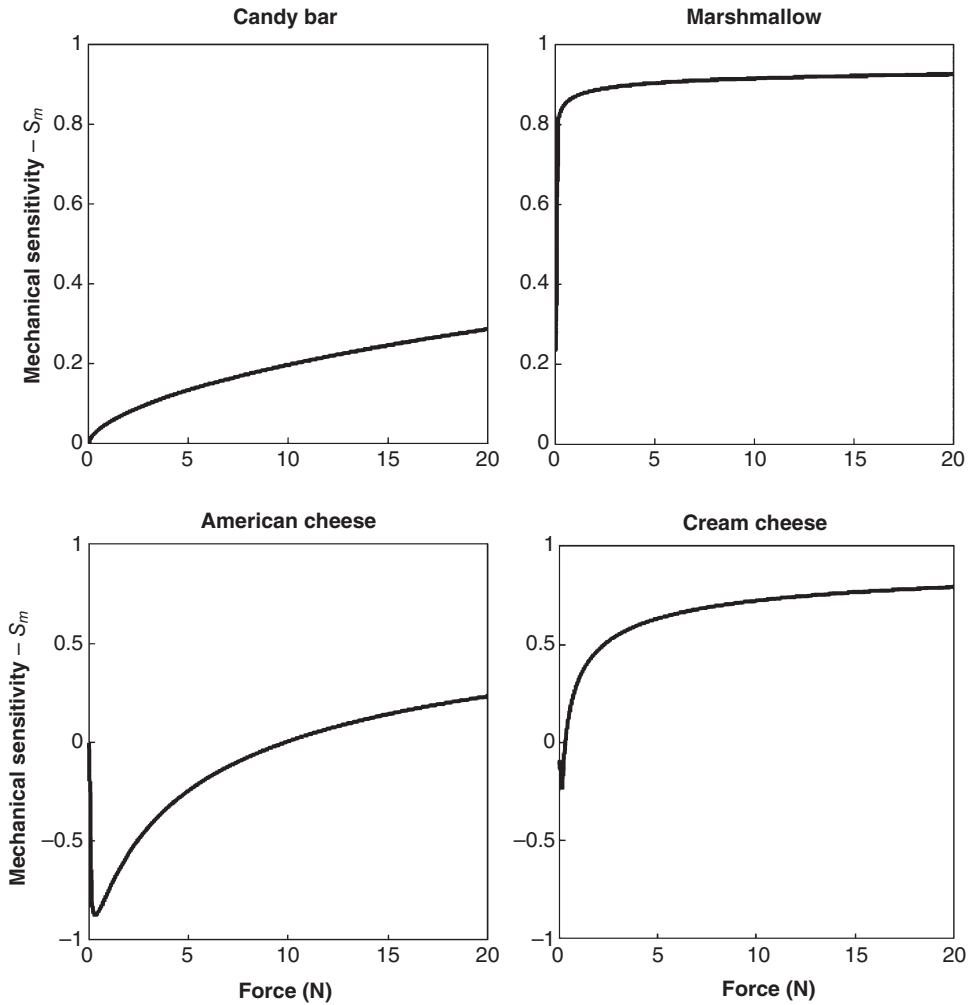


Figure 14.6 Examples of how the oral system's mechanical sensitivity can change as a result of the continuous changes in the mechanical resistances of the food and tongue. After Peleg and Campanella, (1989).

$$I_s = \frac{I_{s \text{ saturation}}}{1 + \exp[k(R_{xc} - R_x)]} \quad (14.4)$$

where $I_{s \text{ saturation}}$ is the saturation level, k a constant representing the curve's steepness at its 'exponential region', and R_{xc} a characteristic stimulus that marks the curve's inflection point. The exact expression is unimportant; it is the relationship's general shape that counts.

Let us assume that the Sensory Sensitivity, S_s , is the product of a term, S_{ms} , that incorporates the R_x/R_m ratio in a similar manner to that of the Mechanical Sensitivity, S_m , but with a different scaling factor, m , for example,

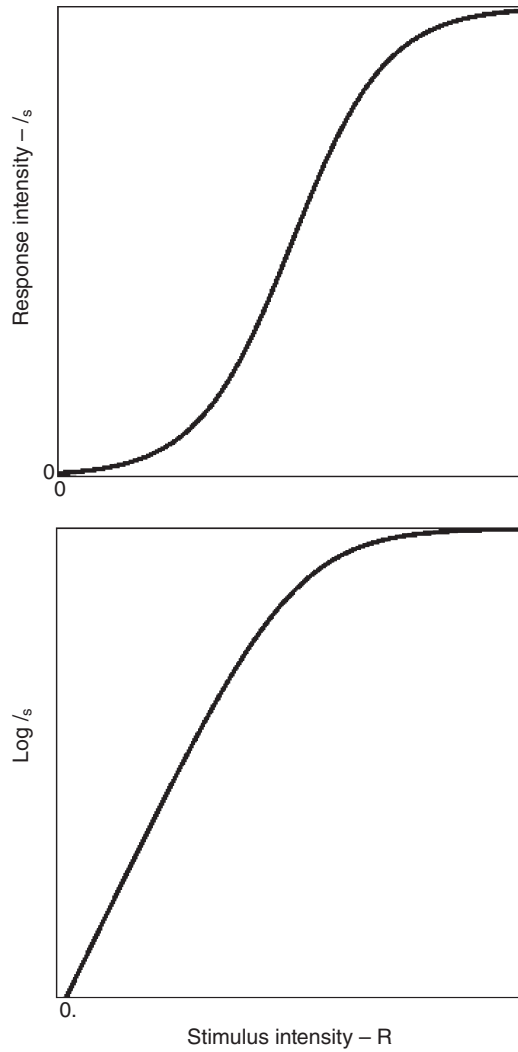


Figure 14.7 Hypothetical sigmoid relationship between the Response Intensity of a sensory system, I_s , to the mechanical stimulus intensity, R_x , generated with Equation 14.4 as a model and plotted on linear and semi logarithmic coordinates. After Peleg and Campanella (1988).

$$S_{ms} = \frac{1}{1 + \left(\frac{R_x}{R_m}\right)^m} \quad (14.5)$$

That is, the Response Intensity will be

$$S_s = S_{ms} \cdot I_s \quad (14.6)$$

Notice that since the tongue's geometry (or the fingers for this matter) might continuously change during the test, the mechanical sensitivity as previously defined might need modi-

fication. If the sensory system's mechanical sensitivity can indeed be represented by Equation 14.5, then what determines the power m will pose an interesting challenge for researchers. At this point, it is just introduced as a theoretical possibility that still needs verification.

If the analysis is valid, the Sensory Sensitivity to a mechanical stimulus generated in the mouth, S_s , could be described by a model of the kind:

$$S_s = \frac{1}{1 + \left(\frac{R_x}{R_m}\right)^m} \cdot \frac{I_s \text{ saturation}}{1 + \exp[k(R_{xc} - R_x)]} \quad (14.7)$$

Plots of this function for four different arbitrary combinations of mechanical and sensory characteristics (marked A, B, C and D) are shown in Figure 14.8. The figure demonstrates that any sensory system that follows Equation 14.7 as a model, even if only qualitatively, has little or no sensitivity when dealing with very soft food materials or very hard (stiff or rigid) ones. In the first case, this is because the stimulus is too weak and in the second because the mechanical sensitivity is close to zero. Thus, although the sensory system has a mechanical sensitivity very close to unity when sensing very soft materials, its discrimination ability is low or close to zero at this region for lack of sufficient stimulus. In other words, although people, including expert panelists, can safely identify a material as soft, they cannot discriminate between very soft samples, unless they (the panelists) have cues from other attributes, such as flavour or appearance. Similarly, at the other end of the stiffness scale, panelists can easily identify foods as being hard because of the stimulus intensity. But they are much less able to feel and identify differences in stiffness without external cues (Peleg, 1980). In between, there is a range of stiffness levels for which the tongue or jaws have their maximum sensory sensitivity. As demonstrated in Figure 14.9, the span of this range and the peak sensory sensitivity are determined by the tissues' own mechanical properties, which control the mechanical sensitivity, S_m , and by the number, density and types of mechanoreceptors and nerve endings, which control the Response Intensity, I_s . There are very few publications that report and discuss the *spread* of sensory evaluations as a function of the mechanical stimulus's intensity. Had they been more common, they would most probably look like the plot shown in Figure 14.9. And since the parameters that determine S_m and I_s are likely to vary among individuals, the scatter in a panel's responses is expected to be wider than that of single panelist (Peleg, 1980). The very few reports with which we are familiar are indeed consistent with this picture (Peleg, 1980). These presumed characteristics of the sensory system's sensitivity to mechanical stimuli, if confirmed experimentally by specially designed tests, would have immediate practical applications in food production and quality control. According to the described model, hard foods like a biscuit, for example, can tolerate large hardness variations (as long as no danger to the teeth exists), and the same can be said about variations in the viscosity of most fruit juices (but probably not nectars). Unless the differences are manifested in other organoleptic properties to which people are more sensitive, it is very unlikely that they will be noticed by the consumer, and therefore their discovery might not be a cause of alarm. This statement should not be construed as a suggestion to eliminate or scale down rheological testing as part of quality assurance (QA) or quality control (QC) programmes. In certain instances a change in viscosity, although innocuous by itself, may be associated with or indicative of other changes in the food that might need attention or immediate remedy. Possible

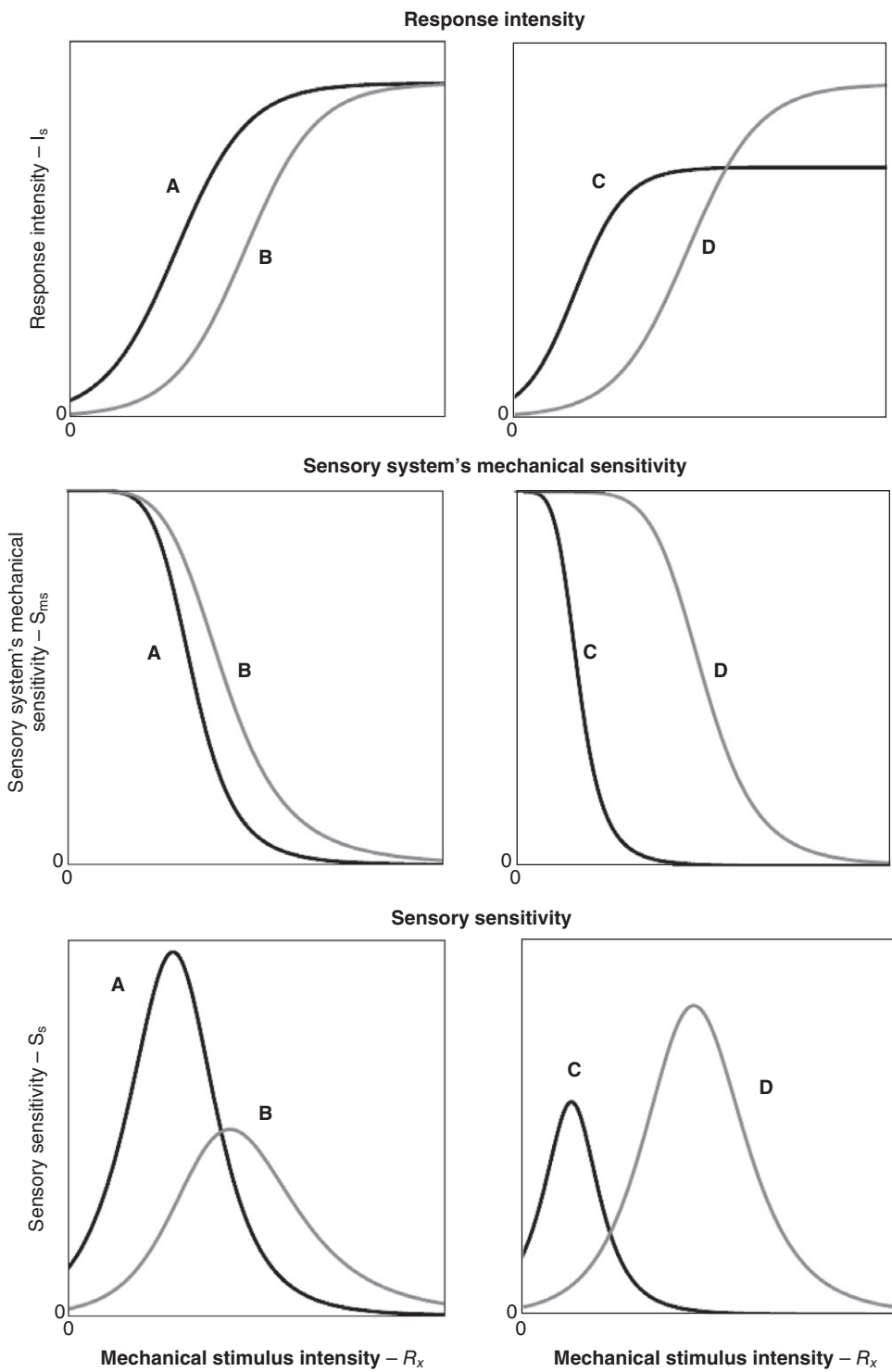


Figure 14.8 Sensory Sensitivity, S_s , vs. mechanical stimulus intensity, R_x , plots generated with Equation 14.6 as a model for four hypothetical cases marked as A, B, C and D. Notice that according to this model the sensitivity peak's location and magnitude depend on the physical properties of the system as well as its neurological. Also notice the absence of sensitivity when the mechanical stimulus is either too weak or too strong.

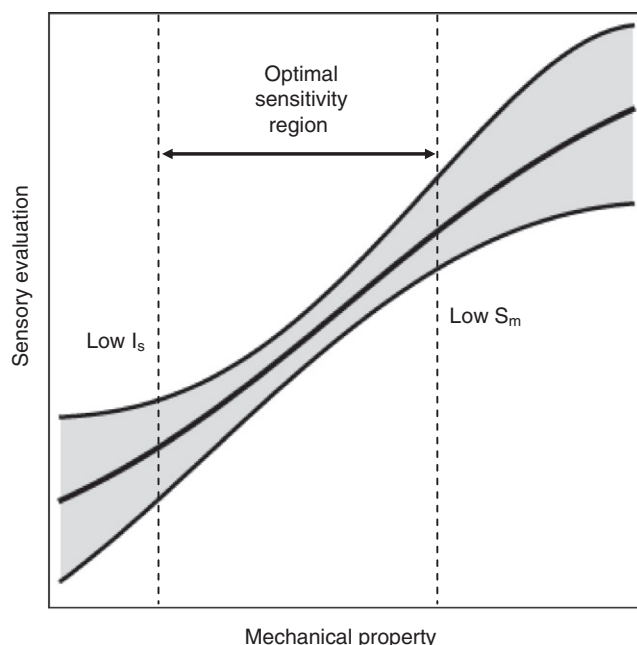


Figure 14.9 Hypothetical sensory response – mechanical stimulus intensity curve (I_s vs. R_x) on which the expected spread has been superimposed. Notice that the smallest spread is expected to coincide with the stimulus, R_x , for which the system has maximum Sensory Sensitivity. As the stimulus magnitude grows or diminishes beyond this point, the spread in the sensory responses is expected to increase. After Peleg (1980).

examples are cloud or emulsion stability in liquids or a tendency to break during handling in solids. The purpose of the statement is to alert those in charge of QC or QA to the possibility that a discovered change in a food's mechanical or rheological properties does not necessarily mean that it will be discovered by the consumer, thus helping them in the *interpretation* of observed deviations from the norm and how to respond to them.

14.5 ADAPTATION AND FATIGUE

When we place a weight on a laboratory balance, its reading remains the same as long as we do not add or remove anything. The same is true for any manmade mechanical testing machine, a fact that is exploited in these instruments calibration. As long as the load remains constant so is the instrument's reading or output. There might be a slight delay in reaching the correct reading but in slow loading or placing a constant load this is rarely if ever an issue. (The machine's response-time can and does become a factor to consider in fast loading or when the recorded force rapidly rise or falls, as during the testing of dry brittle ('crunchy') foods such as cereals.) In contrast, although we always feel the weight of a wristwatch, say, when we put it on, the sensation disappears after a while and most people need to *look* at their wrist in order to verify that the watch is still there. So although the stimulus (the watches' weight) has not changed, our sensory response to it has vanished. This phenomenon is due to what is known as the mechanoreceptors 'adaptation', which

also occurs in receptors of other kinds. The development of adapting mechanoreceptors has imparted great evolutionary benefits. Had we been continuously preoccupied with our own weight, the presence of trees, or background noise for example, we would have been less alert to dangers such as an approaching predator's or a biting insect's presence. Thus the sensory system of most animals has evolved to ignore most external and internal stimuli, unless there is a sudden change in their intensity, and obviously if they cause discomfort or pain.

In mechanoreceptors, adaptation can be due to two factors:

- Mechanical relaxation of the receptors and the tissue around them as shown schematically in Figure 14.3, and in the case of a rate sensitive receptor, the diminishing stimulus. (When the pressure becomes constant the pressure rate drops to zero.)
- Chemical equilibration through ion diffusion, which results in the decrease and eventually the disappearance of the electric potential, which triggers the receptor firing. It is not unreasonable to assume that the sensory response to other stimuli generated during mastication could be similarly affected albeit by other mechanisms. In other words, the continuous manipulation of the food in the mouth is perhaps essential to produce a non-vanishing stimulus that can be perceived. How exactly the sensory system integrates the various receptors responses, is yet unknown, at least to the authors of this chapter.

Most muscles, including those in the jaws or tongue, can experience fatigue. When this occurs, the difficulty to continue the mastication *rises* with time – as in chewing tough meat. However, with few exceptions, a food's mechanical resistance during multiple 'bites' usually decreases as a result of the food disintegration and wetting with saliva. Theoretically, the manifestation of these antagonistic factors on fatigue can assume various forms, depending on their relative rates. Various simulated fatigue patterns based on this notion and their discussion can be found in the work of Roy *et al.* (1989). Again, how they affect the perceived texture of the food is unclear.

All of the above indicates that texture perception through the firing of mechanoreceptors is a continuous process. This raises the question of *when* the information generated and processed in the brain becomes recognised as textural attributes. Or asked in another way, are all the textural properties perceived simultaneously, or at different times, following different modes of manipulating the food in the mouth? The latter seems to be more likely, but how the feedback mechanism works in the presence of non-mechanical stimuli is yet to be revealed.

14.6 CONCLUDING REMARKS

This chapter relies heavily on work done at the University of Massachusetts Amherst in the late 1980s and early 1990s, which focused on very select aspects of the sensory system performance, namely the mechanics of soft machines. Most of the publications cited in this chapter are the results of a project that was supported by the National Science Foundation and afterwards by the Massachusetts Agricultural Experiment Station at Amherst. The objectives of these works did not include most of the other aspects of texture perception and therefore they are only mentioned in the chapter as notes or suggestions for future

studies. Since the time of the project's conclusion, there have been significant new developments in experimental techniques, especially concerning *in situ* measurements of forces and accelerations during mastication and a better understanding of the physiology and neurology of the human sensory system's working. These advances will no doubt improve our understanding of how texture is perceived and shed new light on many of the outstanding issues in sensory studies in general. Also, developments in linguistics might be utilised to clarify the cognitive aspects of texture vocabulary and how they should be considered when interpreting information retrieved from human subjects. To the best of our knowledge, the issues raised in this chapter concerning the role of soft machine's mechanics in texture perception and the need to apply the principles of semantics in the analysis of verbal sensory evaluations have had no impact on the field. However, we still believe that the mechanics of soft machines, which impose physical constraints within which the sensory system must operate, are essential to the proper interpretation of at least certain types of sensory data. This is regardless of how exactly the sensory system translates the assortment of forces, accelerations and acoustic and other signals that are generated in and outside the oral cavity into perceived attributes that we identify as 'textural'. We hope that readers will agree with us on this point and that the issues raised in this chapter will be taken into account in future research on food texture and its sensory perception.

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Part Five

Applications and New Product Developments

15 Appreciation of Food Crispness and New Product Development

Paula Varela and Susana Fiszman

15.1 INTRODUCTION

Texture appreciation is an integral part of an eating experience and is often used by consumers as an important assessing factor for food acceptability. Foods that provide pleasing textural experience are liked by consumers, but those with undesirable or unexpected textural features are often disliked or rejected. Of the various textural features, crispness and crunchiness are probably the two most commonly referred to, appreciated by consumers of all cultural and social-economical backgrounds. In Western countries, the attributes crispy and crunchy top the list of all liked textural characteristics. However, to design and produce a crispy and crunchy food and to maintain its textural features during storage involves many technical and practical challenges. This chapter will review latest research progress on food crispness and crunchiness, the appreciation and instrumental characterisation of such textural features, and the determining mechanical and microstructural properties. The main focuses of the discussion are on crisp wet, crisp dry, and crusted or multi-layered foods and the principles and practices applied in industry in designing and providing such products.

15.2 APPRECIATION OF CRISPY AND CRUNCHY TEXTURE

Attitudes to food choice and consumption are greatly influenced by learned expectations and previous eating experiences, as well as physiological, psychological and socio-economic factors. The modern style of living has increased the consumption of food items where texture is a determinant quality feature. 'Nouvelle cuisine' has led to developments in imparting new textures to traditional preparations or combining various textures in the same dish (foams, gels, emulsions, globules) with the help of lyophilisation, ultrasonic mixing, vacuum cooking and other 'molecular gastronomy' techniques.

The attributes crispy and crunchy are often linked to freshness and high quality of a food (Szczesniak and Kahn, 1971a; Szczesniak, 2002). Historically, crispness has been defined as the ability of a food material to fracture into many small pieces under a compression pressure and has been associated with the brittleness of the food. However, Vickers and Bourne (1976) stated that this was not completely adequate to explain crispness in all

products. For example, an apple appreciated as crispy is not necessarily fragmented into pieces when bitten into. Instead, Vickers and Bourne proposed that the link between the mechanical properties and the perception of crispness was the sound produced during fracture. Drake (1963) was the first scientist to study the sound of food during mastication, but Vickers and Bourne (1976) presented the first psycho-acoustical theory of crispness, a 'cellular model'. They suggested that crispness was caused by cellular structures that produced sound on breaking; this model could explain crispness both in wet-crisp products (living plant cells) and dry-crisp products (products with holes/cells filled with air). Szczesniak and Kahn (1971b) proposed that crispness and crunchiness denoted similar mouth sensations but crunchiness might be applied to moist food. Vickers and Wasserman (1979) found that the sound produced when certain foods were crushed was composed of many pitches and the loudness of the sound varied over these pitches. It was later stated (Vickers, 1984) that crispy foods produced higher pitched sounds than crunchy ones when bitten. Szczesniak (1988) backed this hypothesis but suggested that a food might be crispy and crunchy at the same time.

Very often, the words crispness and crunchiness are used interchangeably and differences between the two are not always easy to describe (Szczesniak, 1988; Mallikarjunan, 2004; Varela *et al.*, 2007a). Some studies have obtained strong correlations between the two terms while others have suggested they refer to different concepts (Roudaut *et al.*, 2002). Translation is another problem, as observed by various researchers. Texture terms used in one language very often have no true equivalent translations in the other languages (Zannoni, 1997; Rohm *et al.*, 1994; Dijksterhuis *et al.*, 2007). English is the language most often used for research papers, where words such as 'crispy', 'crunchy' and also 'crackly' are most commonly used. A polyglot list of textural properties developed by Drake (1989) shows that other languages may have more than one equivalent for the word crispness. Varela *et al.* (2007a) conducted a trans-cultural consumer study involving two Spanish-speaking countries (Spain and Uruguay). It was found that the terms crispy ('crujiente') and crunchy ('crocante') had different meanings or evoked different perceptions in the two countries.

15.3 MECHANICAL AND STRUCTURAL FEATURES OF CRISPY/CRUNCHY FOOD

What is well known is that crispy and crunchy are directly related to the mechanical and fracture properties and, in particular, to the sound produced at fracture (Vincent, 1998; Mallikarjunan, 2004; Varela *et al.*, 2006). It is clear that crispness/crunchiness can be completely different from one product to another. For example, fresh vegetables, fried potatoes or extruded snacks could give very different crispy/crunchy experiences. It is therefore common practice to classify products into wet-crisp (consisting of raw, turgent vegetables and fruits) and dry-crisp (comprising the rest of the crispy foods, including farinaceous, baked and fried products) (Duizer, 2001; Roudaut *et al.*, 2002; Dijksterhuis *et al.*, 2007).

15.3.1 Wet-crisp food products

This category comprises raw and minimally processed fruits and vegetables. For these products, crispy/crunchy features are a consequence of their native structure and constitute an important quality factor of these products (Fillion and Kilcast, 2002; Waldron, 2004). Living plant cells have the property of turgor, where the outward pressure exerted by the

cell contents on the cell wall is balanced by the strength and elasticity of the wall itself. The noise produced when biting a fruit or vegetable is attributed to the manner in which the cell-wall skeleton ruptures. A group of cells might be rupturing at the same time during biting and mastication, producing a series of sounds (Waldron *et al.*, 1997, 2004). A change in cell turgor would mean different sounds could be produced at rupturing. Chemical and physical processes (cooking, drying, freezing, irradiation or storage) can affect the turgor of the cells and lead to textural changes and a loss of crispness (Kunzek *et al.*, 1999). Cell turgidity is highly dependant on the water content. If a tissue has lost moisture through evaporation, as in wilted lettuce, or if the extensibility of the cell walls has increased, then the turgidity will be lowered and tissues will become rubbery and therefore not crispy (Waldron, 2004). Recently picked apples are very crisp, but apples quickly lose crispness during storage due to the solubilisation of pectins in the middle lamella and reduced cell adhesion. Consequently, these cells produce less sound and give a sensation of mealiness. Fruits will be perceived as less crispy, drier and of course less fresh. Nowadays, consumers' desire for unadulterated and more natural foods forces the industry to apply minimal handling and processing to fruit and vegetable products.

15.3.2 Dry-crisp food products

Crispy/crunchy dry products are firm and brittle, producing sound on biting or chewing. These products can be morphologically characterised as cellular solids, with a solid matrix filled with air cells that can be either open (sponge-like structure) or partially closed (foam-like structure) (van Vliet *et al.*, 2007). Edmister and Vickers (1985) categorised foods such as toasts, biscuits, crisps, roasted almonds and flatbread into this group. Szczesniak (1988) classified 'dry-crisp' products as 'farinaceous products', such as crackers, breakfast cereals, potato chips, baked goods (bread, rolls, etc.), toast, cookies and snacks; and 'fried products', such as bacon, chicken, French fries and so on. The aforementioned cellular model as the mechanism of sound production is also applicable for some dry-crisp foods (Vickers and Bourne, 1976). In this case, cells or cavities within a brittle matrix structure are filled with air instead of water. The breaking of a brittle cavity would produce a snap and further vibrations would generate and propagate a sound pressure wave. The stiffness of the vibrating body (the brittle matrix) would determine the quality of the sound; a stiff wall would vibrate more rapidly, produce a louder noise and be perceived as crispier. This model would explain the loss of crispness through hydration, as walls lose their stiffness after absorbing moisture. However in some other foods, such as potato crisps, the cellular model by itself does not explain the sound production. More sound is produced when fracturing those products than expected from a structure of only a few cells thick. In crisps the sound is generated more as a result of the repeated fracture of the thin product, helped by its curved shape (Vickers and Bourne, 1976). The particularly uneven breakdown pattern in this category of products is caused by heterogeneities in the structure, where fracture starts because the stress applied to the material concentrates at those fracturing points. Multiple fracture events are the result of a non-homogeneous morphology. Unevenly distributed microstructural elements such as air bubbles, water or oil phase or composite structures of different hardness can all cause a structural anisotropy. It is hypothesised that, when a dry-crisp material is broken, each fracture event corresponds to an acoustic event (Chen *et al.*, 2005).

Morphology of the structure and the molecular mobility, in particular of plasticisers, are two very important factors affecting crispness/crunchiness in these products (Luyten *et al.*, 2004). Migration of small molecules during storage is the biggest cause of weakened

mechanical strength, decreased glass transition temperature and therefore reduced crispness.

15.3.3 Crusted or multi-layered food products

There is a group of products that behave differently on fracturing: foods have a dry crispy/crunchy crust and a soft high-moisture core (or layer). The mechanical, morphological and compositional differences between the layers make their breaking pattern and mechanical behaviour rather unique (Varela *et al.*, 2008a). Depending on how the crispy crust is originated, this category could be subdivided into three groups: products whose external layers are initially the same as the rest of the food product, but change (composition and microstructure) as the crust develops during the cooking process (potato chips, different kind of breads and other bakery products); products coated with another layer of different material (battered or breaded fried products); and composite products like pizza, pies, filled biscuits or filled pastries.

All crusted products present common characteristics and also difficulties inherent to their particular structure. Obviously such foods have a well defined difference between the core and the crust: different composition (water, oil, starch, protein, etc.), different microstructure, as well as different size and shape. To maintain the crispy/crunchy character for some time after preparation is a major challenge in such foods. In general, the texture deterioration of the crust layer is related to the continuous transport of water from the moist layer to the dry one (Dijksterhuis *et al.*, 2007). It is in principle not possible to completely stop water migration, but any possibility of slowing down the process is worth exploring.

15.4 CHARACTERISATION OF CRISPY/CRUNCHY TEXTURES

15.4.1 Sensory perception and measurement of crispness/crunchiness

Crispness, crunchiness and crackliness are textural attributes strongly linked to the overall acceptability of a food (Chauvin *et al.*, 2008). By using a sensory panel to compare sounds produced by different food, Vickers and Wasserman (1979) reported that the perceived quality of these sensory features correlates well with the loudness of the sound released during chewing. Edmister and Vickers (1985), however, concluded that differences in perception between wet-crisp and dry-crisp foods are not due to a difference in the sound quality, as people could not discriminate the sounds from the two sources. Further works demonstrated that humans can accurately rate crispness in different foods either from the 'vibratory' information only or from the sound only (Vickers, 1991). Crispness would then actually be a vibro-tactile sensation.

The sensory descriptive method has been popularly used by food researchers since the 1980s and is often used as a reference technique for instrumental sensory assessments. However, a big problem in this approach is the variation in organising taste panels, including sample handling (biting with the incisors, chewing with the molars, crushing or snapping with the fingers) and the measuring parameters (structure of the intact product, sound emitted at fracture, force required to crush the sample, how the product collapses etc.). Chauvin *et al.* (2008) even worried about whether the same definition of crispness/crunchiness was applied in different panel tests. A proper approach would be first to work

with consumers to get a 'consensual crispy concept' in the target population. Then a precise definition and references could be used to train panellists (Vallés-Pàmies *et al.*, 2000). However, this is rather difficult to achieve since the degrees (or the extent) of crispness cannot be easily scaled.

The same wording and assessment instructions should be used by different research groups so that results from different groups can be meaningfully compared. Apart from this, the use of different languages and different terms in different countries presents another practical problem (Varela *et al.*, 2007a). Dijksterhuis *et al.* (2007) developed a new sensory vocabulary for crisp and crunchy dry model foods, in Dutch with English translation. Chauvin *et al.* (2008) developed standard scales for crispness, crunchiness and crackliness for dry and wet products. The authors proved there was a perceptual difference between dry- and wet-crisp products.

Nevertheless, perceived texture depends largely on the food being broken down in the mouth. Lenfant *et al.* (2009) described the succession of perceptual events during mastication and showed that a texture pathway could be built for each food. They used Temporal Dominance of Sensations (TDS), a relatively new sensory method that evaluates the dominance of perceptions during an eating process. They showed that, for different breakfast cereals, some common features (such as hardness, crackliness and crispness) were perceived at the beginning of mastication, features such as brittleness and lightness were better perceived during the middle of the process, but the stickiness sensation only became dominating at the later stage of an eating process.

15.4.2 Instrumental characterisation of crispness/crunchiness

15.4.2.1 Texture measurements

Crispness perception is composed of kinaesthetic and auditory cues. Therefore, instrumental methods for crispness evaluation should focus on measuring either one of these properties or their combination (Wilkinson *et al.*, 2000). Measurements of mechanical properties are most commonly used to assess the fracture during eating (Luyten *et al.*, 2003) and parameters obtained from such measurements have been used as indicators of perceived crispness. The most widely used instrumental tests have been large deformation and fracture tests. Small deformation tests, such as dynamic oscillatory tests, although not often used for these kinds of products, would provide valuable information about the molecular basis of crispness (Roudaut *et al.*, 2002).

Regarding large deformation tests, flexure and compression tests are probably the most commonly used methods. These tests mimic certain aspects of the mastication process inside the mouth by applying a high pressure/stress to cause food to fracture or break. Puncture tests using a small diameter cylinder or conical probes are also extensively used owing to their similarity to biting. Such tests are particularly useful for fruit quality assessment. Deformation and fracture behaviour are normally observed as a function of time at a relatively low rate of deformation to allow detailed detection of individual fracture events. The response is usually recorded in the form of force–deformation plot: a curve with a series of sharp force peaks, each corresponding to a fracture event (Figure 15.1). The classic approach focuses on the initial linear part of the force curve to obtain the mechanical properties of the material, such as the maximum compressive force, deformability, the Young's modulus (when controlling the shape and size of the sample) or an empiric elastic module. But for crispy products, the curve after the linear part seems to be more important

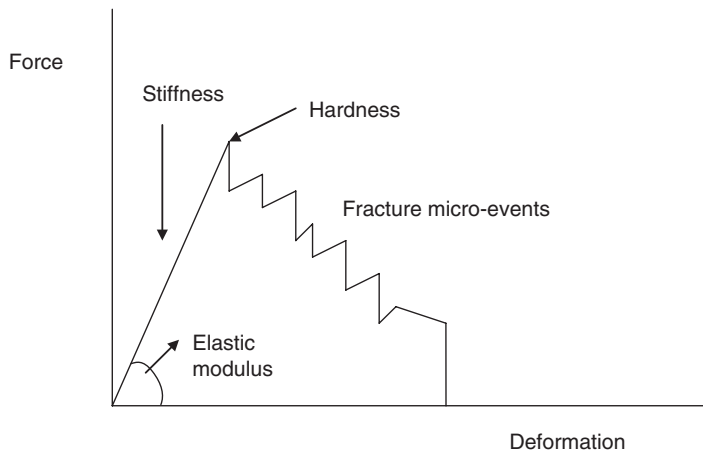


Figure 15.1 A general force–deformation curve for a brittle crispy food item. After the first break up (hardness), the initial fracture travels quickly, with a sudden unloading of the applied force, to be inhibited by heterogeneities of the material.

and relevant. The initial fracture will travel quickly, with a sudden unloading of the applied force, only until it is inhibited by a heterogeneity of the material (fracture arrester). Fracture starts again only as the food is continuously deformed and reaches its yield point. The magnitude of the events is also important. For example, as they become larger and fewer, the texture will be hard instead of crisp, whereas if there are more, smaller fracture events the texture will be crumbly (Vincent, 1998). Based on this, a more recent approach has been to collect information from the jagged part of the force curve, through its shape and irregularities. This method analyses the whole deformation profile and appears to be more appropriate for the characterisation of crispy products (Vallés-Pàmies *et al.*, 2000; Salvador *et al.*, 2002; Luyten *et al.*, 2003).

Fast Fourier Transform (FFT) and fractal analysis have been used to study the multi-peak pattern of the force-deformation plots. FFT analysis determines the power spectrum of a multi-peak line, while fractal techniques study the geometry or jaggedness of a line, quantifying how densely a fractal occupies a space and calculating the ‘fractal dimension’ through various algorithms (Peleg, 1997; Laurindo and Peleg, 2008). However, the validity of these techniques is still under debate. Vincent (1998) pointed out that these approaches did not account for forces and energies, and had no obvious correlation with anything happening in the mouth or to the perception of crispness.

15.4.2.2 Acoustics

For an object to be broken sufficient energy must be available to break the bonds which hold the material together. Fracture starts at heterogeneities because of the locally concentrated stress at weak or defect points. Fracture propagation is related to the energy involved. If a fracture propagates at a high speed, it may give a sound emission. When the crack starts to grow, the energy stored around the tip of the crack becomes available due to stress relaxation. If the amount of energy available exceeds that required for fracturing the crack, propagation continues and audible waves will be formed (Luyten *et al.*, 2003). Heterogeneities

within a material structure (empty spaces, air pockets, defects in the material, oil drops, etc.) act as crack stoppers. Therefore, the overall crack speed is regulated by crack stops and the local energy dissipation. The occurrence of sound emission will depend on both the mechanical properties and the microstructure of the material (Luyten and van Vliet, 2006).

Humans perceive the sound waves produced upon chewing by air conduction, bone conduction and through the soft tissues. The contributions of sounds through different routes have been studied, as well as the dampening effect of the soft tissue (Dacremont *et al.*, 1991; Roudaut *et al.*, 2002). The study of the acoustic input in the sensory perception of crispness has been mainly conducted in two ways: the air-conducted chewing sounds, or combined mechanical tests and acoustic recordings. The air-conducted sounds were studied by playing pre-recorded chewing sounds to subjects and asking them to evaluate their acoustic properties, or by asking subjects to evaluate the sound produced by biting or chewing crispy/crunchy food items. These methods have been useful for developing the definitions of sound-related sensory terms (loudness, pitch, duration of the sound, etc.) and have also stimulated the discussion about what is crispy and what is crunchy. Various mechanical tests have been used to measure texture while recording the sound produced at fracture: flexure (as in three point bending tests), compression, and puncture tests. Some studies have obtained very good correlations between sensory and acoustic parameters, while in some other cases the sound, texture and sensory scores showed poor correlations.

Courcoux *et al.* (2005) used acoustic emission as an objective measure of crispness in cereal flakes and exposed the limitations of previous works with regard to data analysis. For example, the mechanical and sound recordings were not really simultaneous, as the two detectors were not coupled. In 2005, Chen and his colleagues (Chen *et al.*, 2005) showed that the use of an acoustic envelope detector (AED) coupled to a texture analyser was effective in detecting acoustic emission of biscuits at rupture. They found an excellent correlation between the recorded sound and the sensory assessment of crispness. The same method was later applied to crispiness studies of nuts by Varela *et al.* (2006). It was found that that sensory crispness of roasted almonds was highly correlated with the rate and size of acoustic peaks (Figure 15.2).

To be crispy, a product must be stiff and brittle, having a fast fracture (crack propagation) and requiring a low fracture energy (Edmister and Vickers, 1985). Measurements of engineering properties of crispy foods are generally not easy to perform because the size of the food pieces is small compared to that of the inhomogeneities. Structural elements in the crust are usually relatively large compared to the thickness of the coating. Examples include cracks and pores in the crust of a fried product, oil drops and air pockets between core and crust, and those between different layers in a pizza or filled pastry. Additionally, many foods are composed of layers of completely different textured materials. Very often, a soft moist interior is covered or shelled by a dry crispy external layer. Since the dry brittle crust overlies a soft core, the deformation of the food during chewing or biting depends on not only the mechanical behaviour of the crust layer but also the properties of the 'bed' beneath it. Studies related to crispness in products with a highly moist core are so far limited and many were inconclusive (Antonova *et al.*, 2004). Some works have measured the crust in separation from the core part, either by puncturing (Maskat and Kerr, 2002) or using a Kramer shear cell (Ling *et al.*, 1998). Others have measured batter, either fried alone or fried over a metal support and then separated, by puncturing with a cylinder or a conical

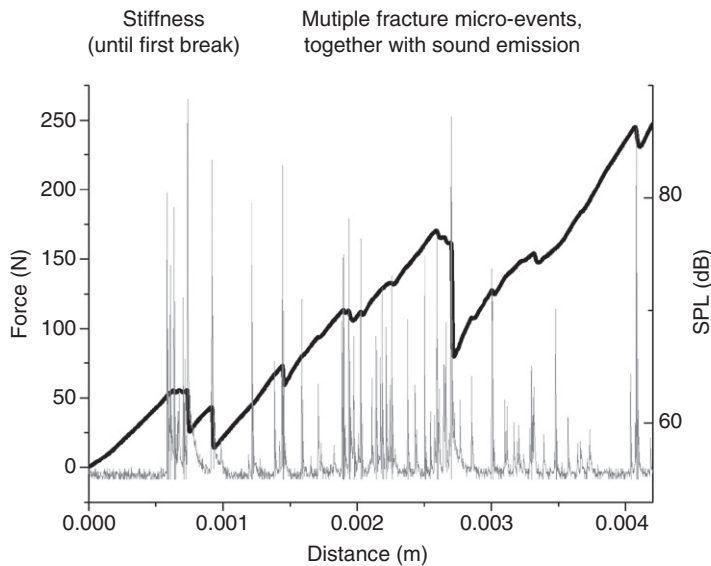


Figure 15.2 Force (black line) and sound pressure level (SPL; grey line) versus compression distance for a roasted almond. After the first break up, a series of new fracture events occurs during the compression, with energy dissipation in the form of sound waves.

probe (Matsunaga *et al.*, 2003). There is no question that these measurements give exact characterisation of the crust layer. However, caution must be taken when trying to interpret these results in relation to the oral sensory experience of such products.

Simultaneous texture and acoustic measurement has become a favoured approach, as has been indicated by Chen *et al.* (2005). Maskat and Kerr (2002) tried to characterise fried chicken breasts with different breading particle sizes by recording the acoustic data during a compression test. Varela *et al.* (2008a) developed a method to assess the texture of crispy crusted foods with a soft moist core, by integrating force–displacement measurement with the sound emission detection. The use of a not-sharp blade was proved to be more appropriate for crispness characterisation of chicken nuggets, giving much better discrimination of differently-cooked nuggets. Albert *et al.* (2009) applied the same method to evaluate microwave-cooked nuggets. It was observed that, even though instrumental measurements gave satisfactory prediction, they were less discriminative than a trained sensory panel.

15.4.3 Instrumental characterisation of crispness – structure and microstructure

Structure, both at macro- and microlevel, plays a fundamentally important role in influencing crispness and crunchiness (Wilkinson *et al.*, 2000). Many researchers agree that studying food structure and microstructure in relation to fracture mechanics and sensory perception in dry-crisp products is of special interest (Varela *et al.*, 2008b). Light Microscopy and Scanning Electron Microscopy (SEM), Cryo-SEM, Environmental Scanning Electron Microscopy (ESEM) and Confocal Laser Scanning Microscopy (CLSM) can all be valuable tools for food structure research. Pascual-Albero *et al.* (1998) used SEM for microstructure studies of roasted almonds. Saklar *et al.* (2003) used light microscopy observation of

roasted hazelnuts. In studying crispness, fracture mechanics and the sound emission of roasted almonds, Varela *et al.* (2006) showed (SEM) microstructural changes of almonds corresponding to texture development during roasting.

Recent advances in image analysis (IA) have added a new value to imaging techniques. Particles, holes, globules and so on can be counted and geometric properties such as area, length, perimeter, sphericity and so on can be precisely quantified to obtain quantitative microstructure information (Aguilera and Briones, 2005; Aguilera and Germain, 2007; Pedreschi *et al.*, 2004; Varela *et al.*, 2008b). Varela *et al.* (2008b) developed a method for quantitative analysis of fracture patterns and microstructure of roasted nuts. LM and SEM were used to follow the changes in the microstructure of the almonds after different periods of roasting. Pictures of fracture particles were taken and particle size distribution was characterised with the help of IA (Figure 15.3). The authors also proposed a method to estimate the extent of the disruption of the internal parenchyma of the roasted nuts. The parameter appears to be relevant to the increased crispness of longer-roasted almonds (Figure 15.4). Dan *et al.* (2007) also used IA for stress analysis of a sheet sensor coupled with a texturometer. The sheet sensor measures planar stress distribution during the compression of crisp food materials. It was found that the stress distribution maps particularly well with the morphology of the food.

Apart from mechanical and microstructural features, many other characteristics such as moistness, roughness, lubrication, size, shape and number of food particles are also very important to sensory perception (Hutchins and Lillford, 1988; Szczesniak, 2002). Therefore,

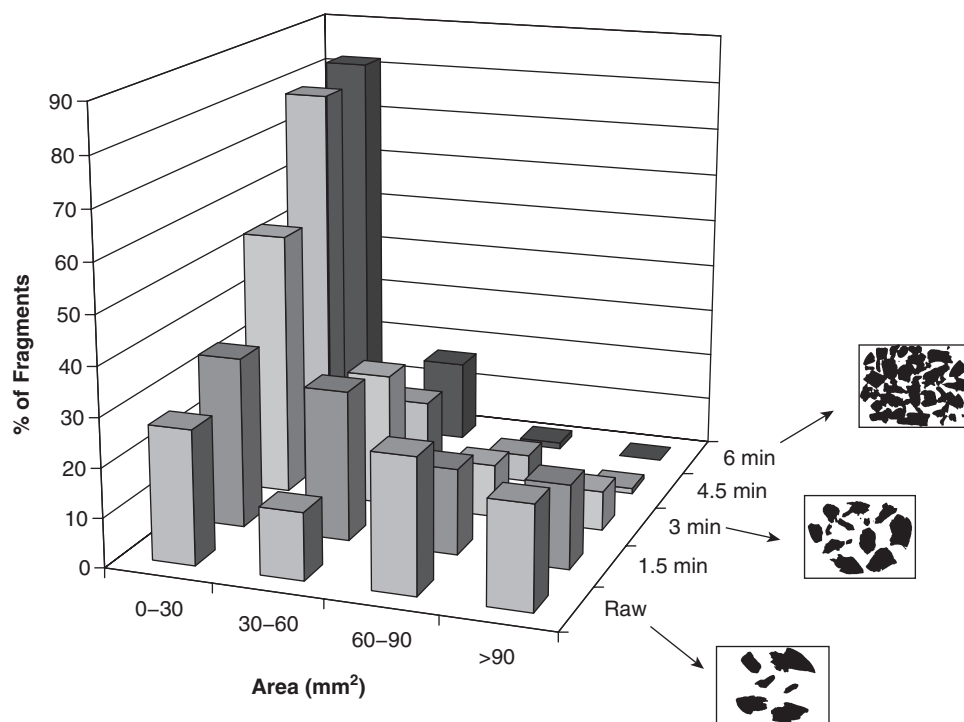


Figure 15.3 Particle size distributions of fractured almonds with different roasting times. Calculation was made by image analysis (Image Pro-Plus 4.5 imaging software, Media Cybernetics, USA). Images of fractured samples with different roasting times are also shown.

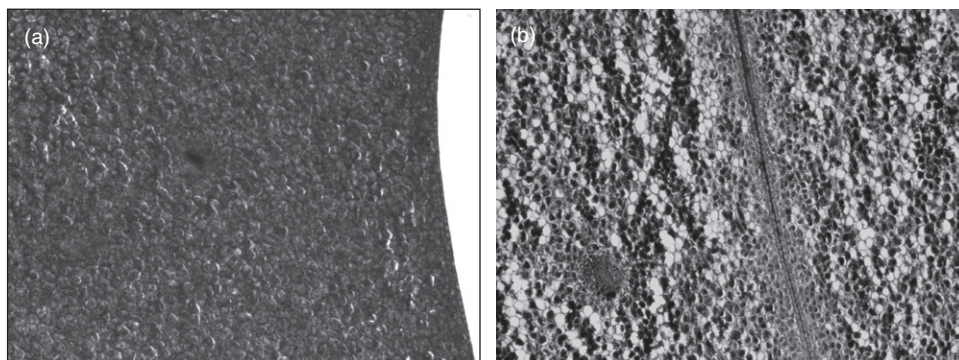


Figure 15.4 Light microscopy of a raw (a) and a 6-min roasted almond (b): inner epidermis and parenchyma (images after processing and binarisation). The white areas can be quantified as a measure of parenchyma disruption (Image Pro-Plus 4.5 imaging software (Media Cybernetics, USA). The highly increased heterogeneous parenchyma in the roasted almond compared to the raw one could be linked to a crunchier texture.

the influence of these factors should also be considered in instrumental characterisation and the interpretation of experimental results. It should also be noted that the perception of texture is a dynamic process. The perceived intensity of a sensory parameter varies throughout the eating process due to the constantly changing textural and microstructural properties of the food. Humans simultaneously detect many aspects of texture and integrate these sensed features into a single perception (Engelen and van der Bilt, 2008; Hutchins and Lillford, 1988).

15.5 INFLUENCE OF THE PRODUCT DESIGN AND FORMULATION, PROCESS AND STORAGE CONDITIONS IN THE ATTAINMENT, ENHANCEMENT AND MAINTENANCE OF THE CRISPY/CRUNCHY CHARACTER IN WET, DRY AND CRUSTED FOOD PRODUCTS

New product development is an extensive and resource-consuming activity in the food industry. The act of first purchase by a consumer is determined by a number of factors external to the product itself, such as package, brand, positioning, price, availability, context and so on, but willingness to repurchase depends greatly on sensory liking and preference of the product. Thus, imparting ‘that change’ to the product is critically important to make the product win over the competitor’s. In terms of crispness, how to make it crispier, or to stay crispy for longer, is a major challenge to food manufacturers and will be discussed in detail in this section.

15.5.1 Wet-crisp products

How a plant tissue deforms during mastication depends on its structural characteristics. These are in turn dependant on the structure and biochemistry of composition polymers,

their cross-linking, cell wall thickness, the interaction of cell contents with the cell wall, cell-to-cell adhesion, tissue structure, and the structure of the organs (Waldron *et al.*, 1997). For wet-crisp products, crispness loss is strongly linked to the biochemical breakdown of the middle-lamellar polysaccharides. The composition of the polysaccharides of the cell wall, their arrangement and how they interact physically and chemically will determine the mechanical properties of the wall, its stiffness and the adhesion between cells.

Additives such as calcium salts will influence the texture of processed fruits and vegetables (Kunzek *et al.*, 1999). These salts can partially restore the mechanical integrity of the cell walls' cementing substances by cross-linking partially degraded pectin chains. Calcium addition has been used for decades in fruit and vegetable canning to maintain or restore crispness and hardness, and more recently in minimal processing procedures (Vickers and Bourne, 1976; Waldron, 2004).

The use of calcium is particularly important in the elaboration of fresh-cut, ready-to-eat fruits and vegetables through direct sale (supermarkets) and wholesale for catering uses (hospitality, air companies, etc.). During mechanical operations, cut surfaces are damaged, releasing enzymes that spread through the tissue and come into contact with their substrates. The softening of fresh-cut fruits is mainly due to enzymatic hydrolysis of cell wall components (cellulose, hemicellulose and pectins) caused by pectic enzymes. Pectinmethylesterase (PME) demethylates pectin, which can be subsequently depolymerised by polygalacturonase leading to cell wall degradation (Alandes *et al.*, 2006). Calcium can interact with the free carboxyl groups to form insoluble salts (calcium pectates) which strengthen the structure of the cell wall, and therefore minimise texture loss (Oms-Oliu *et al.*, 2010).

Calcium chloride is one of the most frequently used salts, although some works reported it imparting bitter aftertaste to the product. In the last few years, other calcium salts such as calcium lactate, calcium propionate, calcium ascorbate or calcium gluconate have been studied as alternative sources of calcium (Gorny *et al.*, 2002). Calcium lactate was reported as not imparting residual taste in the product; at the same time it prevents browning and acts as an acidity regulator (Manganaris *et al.*, 2007). Varela *et al.* (2007b) showed that the use of calcium chloride on Fuji apples maintained the overall acceptability of the fresh-cut product for at least eight days of storage. Although a trained panel detected a significant rise in astringent aftertaste in the treated samples, this had no effect on the consumer's liking. It has been reported that the combination of calcium chloride treatment with low oxygen concentration packaging enhanced the effect of calcium salts; this treatment has been tried on melons, pears and apples over several weeks of storage (Oms-Oliu *et al.*, 2010).

To improve the quality of fresh-cut fruits, various surface treatments have been proposed. One method of surface treatment is to dip fruit pieces into solutions usually containing calcium salts, antimicrobial agents, antioxidants (to prevent enzymatic browning) and other functional ingredients. In the past few years, however, one of the major advances in increasing the shelf-life of fresh-cut products has been the application of edible coatings. These coatings are generally composed of macromolecules such as carrageenan, alginate, gellan, methylcellulose, starch, chitosan and whey protein concentrate (Oms-Oliu *et al.*, 2010). Polysaccharide-based coatings are normally applied to fruit pieces as a first step treatment, followed by a second step of dipping into a solution containing the anti-browning agents as well as calcium salts for instant cross-linking and gelation of the coating layer (Lee *et al.*, 2003). This practice helps to minimise the loss of crispness of fresh-cut apples and melons. In alginate- or gellan-based coatings, the use of calcium chloride was reported to prevent moisture and turgidity loss of fresh-cut apples (Rojas-Graü *et al.*, 2008). The

use of calcium chloride together with anti-browning agents within a whey protein concentrate-based coating showed a great benefit in maintaining the firmness of apple pieces (Lee *et al.*, 2003).

Fresh-cut fruits are more difficult to process than fresh-cut vegetables due to the fact that some fruits must be ripened before they are processed. The importance of previous history of fruit prior to processing has been studied by the authors' research team. It was found that the changes of apples and pears at ambient conditions were quite different, dependent on whether they were previously stored in cold/controlled atmosphere or had been recently harvested. Prolonged storage caused changes in the fruit that led to a shorter sensory shelf-life (Varela *et al.*, 2005; Salvador *et al.*, 2007; Varela *et al.*, 2008c).

15.5.2 Dry and crusted products

Dry-crisp food items suffer sensory deterioration after contact with a high moisture layer. This is because dry and composite products are not at their equilibrium state and will have a lower moisture content (or water activity) than that of the surrounding environment (e.g. breakfast cereals, extruded snacks, crackers), or of the contacting humid layer (e.g. pies, bread, fried products). Water will then be prompted to migrate from a higher content location to a lower, and the loss of crispy character would be directly related to the kinetics of water uptake. Maintaining crispness during the shelf life or during the consumption window is a great challenge. An integrated approach including formulation, packaging and storage is needed in order to maintain sensory crispness over the longest possible period.

The formulation and use of appropriate functional ingredients are probably the most important factors for food crispness. For example, the type of flour or the use of gums in extruded snacks, the use of emulsifiers or enzymes in baking, or adding different hydrocolloids to coatings for crusted products, as well as the interactions between different ingredients, all play a role in the crispness creation of the final product (Roudaut *et al.*, 2002). In processed products, molecular mobility and the content and distribution of plasticisers are key factors in attaining the crispy/crunchy texture during storage. Plasticisation generally increases the mobility of small molecules in the material, which leads to decreased glass transition temperature and reduced hardness and stiffness of the product. Redistribution of plasticisers in the product can cause the structure to swell and a transformed morphology. Lipids and other low molecular weight components can also have similar functionalities as plasticisers and therefore influence food texture. In addition, complex compositional changes in the food matrix, such as starch retrogradation, may also play a very important role in the crispness sensation of dry and crusted foods (Roudaut *et al.*, 2002; Luyten *et al.* 2003; Varela *et al.*, 2008a).

15.5.2.1 Bread as an example of composite crisp food

French style bread is a typical example of crusted crisp food which contains a relatively moist crumb core. After baking and during storage, water migrates from the moist crumb to the crust, diffusing into the dry solid polymeric matrix. For a glassy matrix system as the crust initially is, Fick's law dominates the first steps of the process (concentration gradient controlled), followed by a swelling of the matrix with a redistribution of the free spaces to be occupied by water. Van Nieuwenhuijzen *et al.* (2008) evaluated the sorption kinetics

of water uptake in bread crust and showed that sorption could be described by a single exponential function of time, with water uptake rated as one of the fitting parameters. They found that maximum water uptake was at RH 50–70%. Further experiments raised the question of whether it is the amount of water absorbed or the water activity (a_w) that leads to a loss of crispness (van Nieuwenhuijzen *et al.*, 2009)? They studied the effect of both parameters on the glass transition in model bread, finding that the water content of the crust was the determinant of the glass/rubbery transition point, but both water content and a_w had an effect on the crispness.

It was also observed that the transition from crispy to non-crispy depends as well on the speed of sample deformation (Castro-Prada *et al.*, 2009). The brittle-to-ductile change starts at a lower a_w for a slow deformation speed than that at a higher speed. This means that people with different mastication speeds would perceive texture differently, and probably consumers accept to a different extent the quality loss of crispy foods.

Another very important factor affecting crispy texture in bread is the structure of wheat starch in the crust. The changes in crystallinity are technologically important, as they result in perceivable sensory changes that can happen in a relatively short period of time (in few hours). Native starch is present in flour as semi-crystalline polymers organised in granules. During baking, the starch is gelatinised in the presence of water and heat, resulting in a final amorphous structure in the bread crumb. During storage, a crystalline structure of the starch slowly appears due to staling, principally affecting the crumb. Primo-Martin *et al.* (2007) studied the effects of storage on the state of starch in the crust, finding that the process of staling is different to the one happening in the crumb. Amylopectin retrogradation, responsible for the staling of bread crumb, cannot be responsible for crispness deterioration of the crust as it can only be measured in the crust after two days storage, while loss of crust crispness proceeds over a much shorter times (within hours).

A modification of the macromolecular network of the crust can be used to regulate its water holding capacity. The gluten network can be modified by the use of enzymes, such as proteases. These have been used in bread making to obtain crusts that stay crisper for longer (Primo-Martin *et al.*, 2006). Packaging also plays a role in preventing water loss or moisture uptake after baking, however it has a limited use for crispness retention. Breads such as French styles are normally packed in oriented polypropylene bags, perforated with small holes. The package allows moisture passing from the crumb to the crust to escape and helps to retain crispness. If the pack is too impermeable to moisture, the crust would quickly become soggy (Robertson, 2006).

15.5.2.2 Deep fried products

Deep fried products, such as directly fried (e.g. French fries) or battered/breaded before frying (e.g. nuggets or fish fingers), are also interesting examples for the understanding of the parameters affecting crispy crusts. The main role of the outer crust is to act as a barrier against moisture loss, protecting the natural juices of the food substrates during cooking, freezing or reheating. But the crust is also an important quality feature. The final cooking, generally by deep frying, leads to a product that is tender and juicy on the inside and crisp on the outside (Fizman, 2008). The effect of water or lipids as plasticisers could be misunderstood if they are considered as total contents in the whole product without taking into account their distribution in the different layers (Luyten, *et al.*, 2003, 2004). Although the

moisture and fat contents of the core and crust have been found to be related to the texture characteristics, products with similar moisture contents in the crust can have very dissimilar textures, showing that crispness would depend on the water distribution within the thin crust layer (Varela *et al.*, 2008a).

In deep fried products, suction of oil into the crust may happen as a result of the lower pressure formed in the pores due to water vapour condensation when the product is cooling down. This process does not affect the rate of crispness loss by itself. However, the amount of oil in the crust influences the perceived crispness and affects the sound emission at fracture. Van Vliet *et al.* (2007) explained that, because of the reflection of the sound at the oil–air interface, a larger amount of oil in the air pockets makes the crust layer more homogeneous and dampens the sound. Crispness of fried foods could potentially be improved by decreasing the amount of oil that is absorbed during frying. Nowadays, coatings (breading and batters) can be formulated for improved functionalities, such as reduced oil intake, improved cohesion of the external layer, better adhesion to the substrate, enhanced crispness/crunchiness in the crust and so on (Albert *et al.*, 2009). Hydrocolloids have been studied thoroughly for their performance and advantages in coating systems. The replacement of wheat flour by flours from other sources, as well as the use of protein isolates and dextrins, has been investigated for possible benefits in improving coating performance. Corn, barley, rice, potato, tapioca, soy and pea flours have also been reported to be able to reduce oil uptake and to improve crispness retention, particularly when combined with hydrocolloids such as xanthan gum or methylcellulose.

The addition of starches from sources other than wheat could also be a possible means to improve crispness. Starches of different amylose/amylopectin contents, as well as the size and composition of the granules, could be used to optimise the swelling and gelatinisation profile. Improved crispness is generally associated with the use of amylose-rich hybrid starches and the use of pregelatinised starch (Fiszman and Sanz, 2010). Polysaccharide gums are frequently used in battered products, mainly for their viscosity control. The gums that are most often used are xanthan gum and the cellulose derivatives carboxymethylcellulose (CMC), methylcellulose (MC) and hydroxypropyl methylcellulose (HPMC). The use of cellulose ethers that possess the unique property of reversible thermal gelation has been widely investigated as fat barriers. In contact with hot oil MC and HPMC help to gel in the batter layer, leading to lower oil absorption and a greater moisture reduction in the crust (Albert *et al.*, 2009). The use of dextrins in batter formulations has been associated with an improvement in the crispness of the final products, as well as the crispness retention for longer periods (Fiszman and Sanz, 2010).

Microwave cooking has been increasing in recent years for breaded and battered foods. However, the texture developed from microwave cooking is normally unsatisfactory. When a crusted food is microwaved, the moist interior is heated up causing a ‘water pumping’ effect, due to the raised internal vapour pressure. The internal water is forced to the surface surrounded by ambient temperature air, where it condenses and moistens the crust (Albert *et al.*, 2009). An interesting development that can be applied to microwave heating of pre-fried products is the use of susceptor packaging materials. These multi-laminated materials change the pattern of product heating to counteract problems associated with cooking in microwave ovens. When a susceptor is used it generates heat outside the food piece (about 200 °C) to prevent the wetting of the crust by allowing moisture evaporation at the surface (Varela *et al.*, 2008a; Albert *et al.*, 2009). This technique has already been applied for a number of commercial products, particularly those microwaveable ‘ready to heat’ crusted or composite foods (e.g. sandwiches, pastries, pizzas, etc.).

15.6 CONCLUDING REMARKS

Crispness is a much appreciated texture character perceived by many consumers as an indication of the freshness and quality of a food product. Creating and maintaining the desirable crispy texture, however, is a very complicated task. Through critically reviewing the latest research developments in areas of crispness creation, perception and measurements, this chapter provides a foundation for better understanding of the nature of crispness and useful guidance to researchers in the food industry in the designing and manufacturing of crispy food products. Good practices and approaches summarised in this chapter can be adopted by the food industry, including the use of functional ingredients, well controlled processing and cooking, appropriate packaging and storage and so on. Readers should be aware that even though crispness and crunchiness are common terms used to describe all sorts of food products, the creation, characterisation and also the perception of these textural features can be hugely different for different types of foods such as wet-crisp, dry-crisp, crusted and multi-layer foods. Therefore, different strategies are needed for dealing with these food products.

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16 Design of Food Structure for Enhanced Oral Experience

Adam Burbidge

16.1 INTRODUCTION

This chapter is split in to three broad sections. In the first, we review the biomechanics of oral stress and strain perception and consider the resolution limits of the various biomechanical transducers which are present. Later, in the second part, we consider what kind of structures would interact with these mechanoreceptors in an oral context; and finally, in the third section, we consider some potential routes for creating these kinds of (micro)structures in a food context.

16.2 BIOPHYSICS OF ORAL PERCEPTION

In order that we can think about the design of foods for textural stimulation, it seems logical that one should first consider in a little more depth the question of how texture is perceived. There is considerable confusion in the literature due to fairly loose usage of the terms 'texture' and 'structure'. Often these terms are used interchangeably, but in the current context I will define the terms as follows:¹ 'structure' will be defined as the inherent organisation of a material and as such is a material property that can be measured in an objective manner by an instrument. This 'structure' can exist at any lengthscale from molecular to macroscopic, and is often a very complex hierarchical cascade. In contrast, 'texture' will be defined as the brain's subjective interpretation of a material structure based on information provided by the senses. By this definition, 'texture' is a subjective term and, as such, two individuals may well perceive a different texture from the same structure. One advantage of this definition is that 'structural' questions are reduced to material science, and textural questions become those of psycho-bio-physics. Further discussion of material structuring will be postponed to Section 16.4. In the following, we take a closer look at the senses that provide information to the brain.

If we consider the classical five senses of vision, hearing, taste, smell and touch, it is clear that they all provide information about food, both before and during the eating

¹This is not a universal practice, so it would be dangerous to assume that this convention applies to other articles.

experience. What is perhaps less obvious is that each of these senses provide clues about material texture. For example, the smell of freshly baked bread generates a certain expectation of texture. We can immediately see that understanding the stimuli provided to the brain is an incredibly complex problem, and this is one of the reasons that sensory science is so difficult. For the sake of making some kind of progress, the rest of this article will concentrate on touch related stimuli only, but it should be clear to the reader that this in itself is not enough! Touch is a general term relating to contact-induced mechanical stimuli. In terms of mechanics this means stresses and strains of the soft tissue, which must be measured by something in order to provide information. In fact there are at least four known types of so called 'mechanoreceptors', which are specially adapted cells that do exactly this. Before we move on to discuss these mechanoreceptors in a little more detail, it is interesting to make the observation that there is, at least to my knowledge, no method of directly measuring stresses. Stress, in itself, is just a potential to create a deformation, and as such is impossible to observe, although of course one can observe a strain. If one knows the strain and has a good material constitutive model then one can imply the stress required to generate the observed deformation. In the case of small deformations of perfectly elastic materials such as a spring, wire or piezo crystal, the stress is linearly related to the strain by the modulus and this calculation is easy. However, in the case of soft biological materials, which are almost universally non-linear, reactive² and subject to large deformations, it becomes almost impossible to imply the stress in a reliable manner.³

Mechanoreceptors are, in effect, therefore, biomechanical strain gauges, which are actually built around small nerve fibres (either type II or type III respectively 6–12 μm and 1–5 μm in diameter). In the case of type II fibres, these are often encased in some external cellular apparatus. In the medical literature, mechanoreceptors are generally classified into fast or slow responding, and local or long range sensors. I prefer instead to consider the structural features of the individual mechanoreceptors and imply their behaviour based on biophysical arguments. As we shall see, these two points of view are broadly consistent in their conclusions. The four most commonly occurring types of mechanoreceptor are: Ruffini endings, Meissner corpuscles, Pacini corpuscles and Merkel discs. The prevailing medical view of these structures is briefly summarised as follows:

- *Ruffini endings* are largish bundles of nerve fibres located deep in the soft tissue (Figure 16.1).
- *Meissner corpuscles* (also called tactile corpuscles) are coiled nerve fibres present in the individual papillae, sensitive to light touch (Figure 16.2).
- *Pacini corpuscles* are nerve fibres suspended in a fluid-filled cavity inside a multi-layer, onion-like capsule of about 1 mm diameter. They are sensitive to high frequency vibrations and are deep in the soft tissue. Optimal frequency is apparently 250 Hz with a very large field of sensitivity (Figure 16.3).
- *Merkel discs* are strain sensitive structures situated at the interface between the epidermis and the dermis. They appear to be clusters of nerve endings.

²In the sense that the state of the internal musculature at any particular point in time will vary, and, as a consequence, so will the effective modulus.

³One exception to this rule is biting force between teeth, which are themselves reasonably rigid and have been measured by many individuals (Throckmorton *et al.*, 2009).

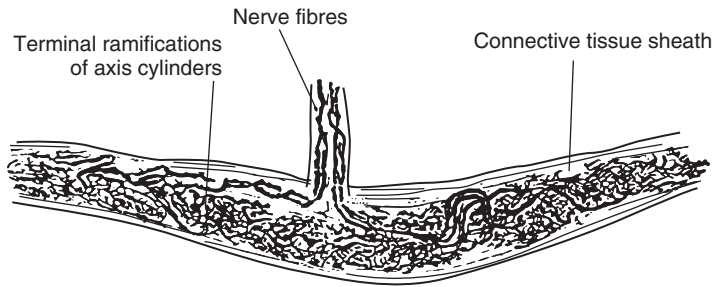


Figure 16.1 Nerve ending of Ruffini (Davies and Davies, 1964).

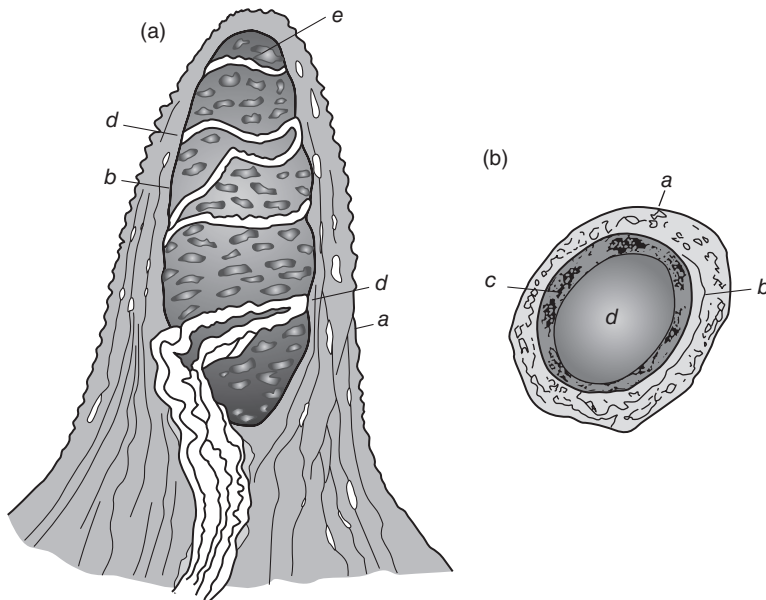


Figure 16.2 Papilla of the hand, treated with acetic acid. Magnified 350 times. (a) Side view of a papilla of the hand. a. Cortical layer. b. Tactile corpuscle. c. Small nerve of the papilla, with neurolemma. d. Its two nervous fibres running with spiral coils around the tactile corpuscle. e. Apparent termination of one of these fibers. (b) A tactile papilla seen from above so as to show its transverse section. a. Cortical layer. b. Nerve fibre. c. Outer layer of the tactile body, with nuclei. d. Clear interior substance. Reproduced from Davies and Davies, 1964, with permission.

Consider the effect of the distance of the mechanoreceptor structure from the force stimulus that it is measuring. The simplest, remotely realistic, mathematical model of this is that of a point load on an infinite half plane of incompressible material of constant elastic modulus.⁴ Assuming that inertial effects can be neglected at this small scale, which seems entirely reasonable, we need to solve the following equation

⁴As already mentioned, this fails to consider the non-linearity of the real soft tissue material, but it gives a good feel for what might happen in the real system.

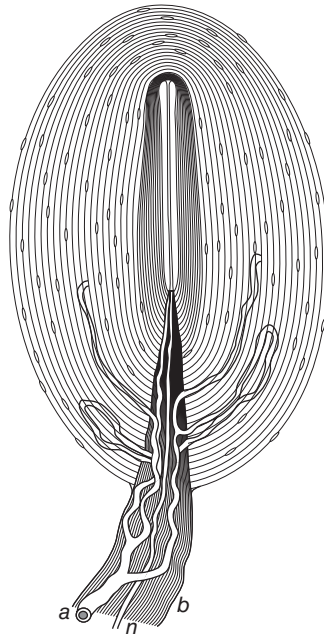


Figure 16.3 Pacinian corpuscle, with its system of capsules and central cavity. a. Arterial twig, ending in capillaries, which form loops in some of the intercapsular spaces, and one penetrates to the central capsule. b. The fibrous tissue of the stalk. n. Nerve tube advancing to the central capsule, there losing its white matter, and stretching along the axis to the opposite end, where it ends by a tuberculated enlargement. Reproduced from Davies and Davies, 1964, with permission.

$$G\nabla^2 \mathbf{u} = \mathbf{F}\delta(\mathbf{x} - \bar{\mathbf{x}}) \quad (16.1)$$

where G is the shear modulus and $\mathbf{u}$ and $\mathbf{F}$ are respectively the displacement and point force vectors.⁵ This is the Boussinesq problem, which has a known Green's function solution describing the displacement vector field u_i for a point normal force F_j at the origin normal to the 3 (i.e. normal to the plane of the contact) direction.⁶

$$u_i = \frac{F}{4\pi Gr} \left\{ \delta_{i3} + \frac{x_3 x_i}{r^2} \right\} \quad (16.2)$$

with r and x_i respectively the scalar radial distance and the vector from the origin. Recalling that the mechanoreceptors actually measure strain, we need to differentiate this equation and take the symmetric part in order to derive an expression for the strain field. The result is

⁵Note that the units here appear not to balance, but actually both sides need to be integrated over the volume $d\bar{\mathbf{x}}$, which then balances the units due to the somewhat strange properties of the Dirac delta function (which actually isn't really a function at all . . . hence the problem!)

⁶<http://www.engin.brown.edu/courses/En224/halfspace/halfspace.html> [accessed 6 October 2011]

$$\epsilon_{i,j} = \frac{1}{2}(u_{i,j} + u_{j,i}) = \frac{F}{4\pi Gr^3} \left\{ \delta_{ij} x_3 + \frac{x_3 x_i x_j}{r^2} \right\} \quad (16.3)$$

Just looking at the form of this equation we immediately see that the magnitude of the strain field is scaled by the inverse modulus of the material and is inversely proportional to the square of the distance from the point force. We therefore conclude that the Meissner corpuscles should, theoretically at least, be the most sensitive of the mechanoreceptors, closely followed by the Merkel discs, since these are the two receptors positioned closest to the stimuli. In contrast, the Ruffini endings would be expected to be much less sensitive. The flip-side of this is that the Meissner corpuscles and Merkel discs are very local in their range; whereas the deeper structures such as Ruffini endings and Pacini corpuscles are somewhat longer range. Figures 16.4 and 16.5 model the transmitted elastic strain field due to a point source at the origin that would be observed by a virtual sensor positioned on a plane respectively $10\mu\text{m}$ and 1mm below the source. In both cases the reference level is set such that 0dB is the signal level when the sensor is $10\mu\text{m}$ directly below the source. The shapes of the two curves illustrate very well how the size of the receptive fields are dependent on the positioning of the sensor in the soft tissue. What matters here are the dynamic ranges of the signals, which are respectively about 80dB ($1:10^8$) and 20dB ($1:10^2$) for the close and the deep sensors over a 4mm square. For comparison, the human ear has a frequency dependent dynamic range of about 140dB .⁷

We can draw a mechanical analogy between the functioning of the Meissner, Merkel and Ruffini structures and that of a classical resistance wire strain gauge. Strain gauges have the advantage of being permanently calibrated to fixed reference, but are quite slow. Consequently, it is often desirable to use a piezo, charge integrating device, which is very fast, but suffers from a lack of a fixed reference point. These integrating devices are particularly useful for measuring fluctuating, or transient strain fields. Pacini corpuscles appear to be an extremely elegant biomechanical implementation of this kind of sensing device. Consider the structure of a Pacini corpuscle (Figure 16.3). The key feature of interest to our discussion is the central fluid-filled cylinder with a fine nerve fibre running through the centre.

We can build an approximate mathematical model of this fluid-filled cylinder (Figure 16.6). In this crude model, the elastic fibre is not coupled to the outside of the cylinder except via the fluid-filled cavity. The dynamical strain field in the far field, which is assumed to cause displacements of the surface of the outer cylinder, is applied as a boundary condition and we use the model to predict the strain on the central fibre. The effect of this 'transfer function' is shown in Figure 16.7 which illustrates the simulated stimulus (the upper curve that fluctuates very slightly around a nominal amplitude of 1) and response (which fluctuates strongly about a nominal amplitude of 0). The fluid-filled cylinder acts as a very effective high pass filter, the characteristics of which are dependent on the shape of the cavity, viscosity of the fluid and elasticity of the fibre. Based on this analysis, one imagines that Pacinian corpuscles, or indeed similar kinds of structures⁸ are very sensitive

⁷dB refers to decibel, which is a common unit for measuring ratios. Here we define it as $10\text{Log}[\text{signal}/\text{reference}]$.

⁸There are no Pacinian corpuscles in the oral mucosa, since they are generally attached to hairs – which are indeed very sensitive to air currents etc. However, given the fact that nature has 'designed' such an elegant and efficient dynamical sensor, it seems hardly credible that there are not other structures that function in a similar fashion somewhere in the oral cavity.

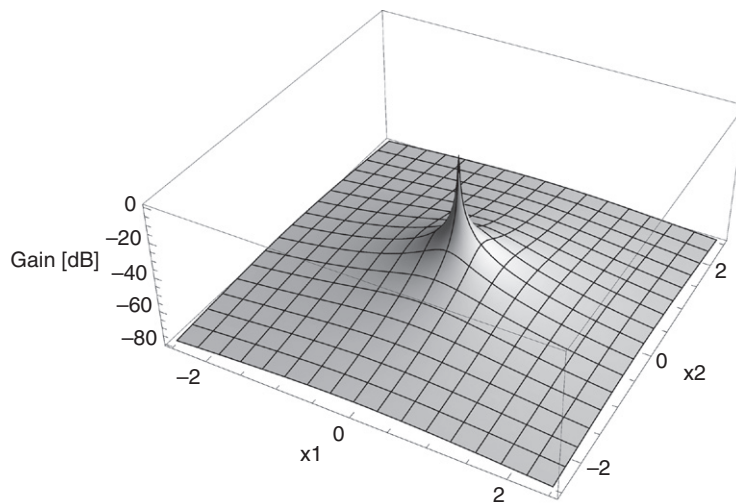


Figure 16.4 Strain sensitivity (ϵ_{33} component) of a notional mechanoreceptor positioned at (0; 0; $-10\mu\text{m}$) to a point force applied in the plane of (x_1 ; x_2 ; 0). Scale is in decibels relative to stimulus directly above the sensor e.g. (0; 0; 0) with x_1 , x_2 in mm.

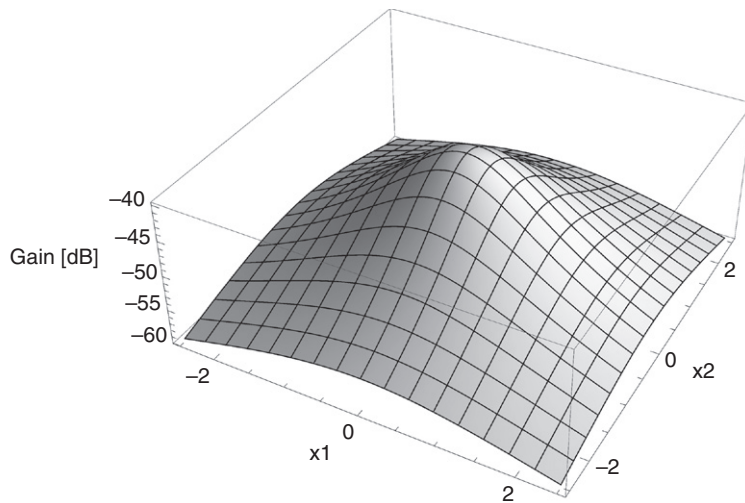


Figure 16.5 Strain sensitivity (ϵ_{33} component) of a notional mechanoreceptor positioned at (0; 0; $-1000\mu\text{m}$) to a point force applied in the plane of (x_1 ; x_2 ; 0). Scale is in decibels relative to stimulus directly above the sensor, e.g. (0; 0; 0) as seen by a mechanoreceptor positioned at (0; 0; $-10\mu\text{m}$). x_1 , x_2 are in mm. Note the narrower dynamic range of 20 dB (which is 100 $\times$) compared to the shallow sensor (Figure 16.4) which has 80 dB (which is 10⁸ $\times$)!

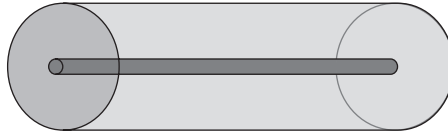


Figure 16.6 Simple schematic for a model of a Pacini corpuscle.

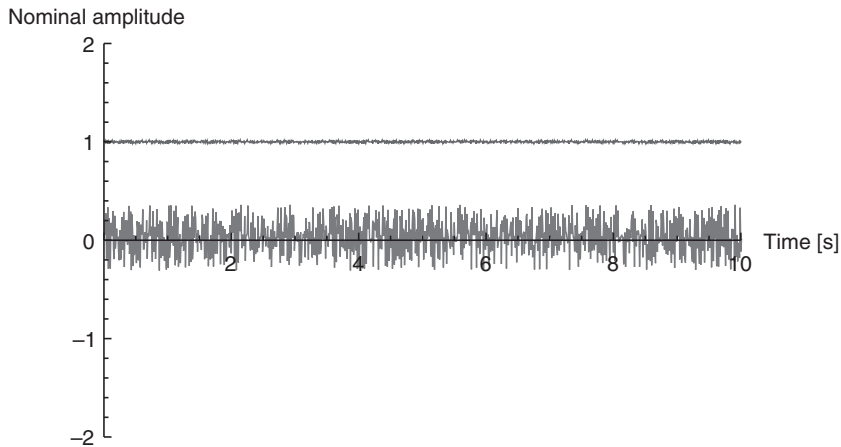


Figure 16.7 Schematic predicted response for a virtual Pacinian corpuscle. Higher trace is the stimulus in the far field, composed of a background stress and noise overlaid at about -25 dB; Lower trace shows the predicted response of the virtual corpuscle which is modelled as a high pass filter with a rejection that drops off linearly with frequency.

to dynamical strains, and effectively ignore steady stimuli, which seems to be the case (Iggo and Muir, 1969).

16.3 STRUCTURAL STIMULI OF MECHANORECEPTORS

Following the discussion of the previous section, in which we established some mechanically based hypotheses describing the functioning of the mechanoreceptors in the human body, we can move on to consider the key question of this chapter, which is ‘how do structured (food) materials, interact with, and stimulate, the texture sensing apparatus in the oral cavity during the eating experience’?

There are several levels of complexity to think about in the context of what has gone before. The simplest place to start is with the ‘smoothness’ of the material under consideration. In this context, smoothness is taken to have the mathematical and not the sensorial meaning. For example a mathematically smooth function is one without any discontinuities that has a well behaved derivative at all points. The reason to choose to start with mathematically smooth materials is that we can then use the available mathematical machinery that is broadly defined by the heading of continuum mechanics, including fluid and solid

mechanics, which will be the most useful in the current context. There have been many developments in these fields in the last couple of hundred years, and as such there are a number of useful results available ‘off the shelf’ so to speak. In addition, there is a sound basis of understanding regarding how these solutions are affected by changes in boundary conditions, material properties and so on.

The simplest class of materials to deal with are those which are incompressible, which includes most fluids and ‘soft’ elastic solids.⁹ In the case of elastic materials, solutions are relatively simple to obtain for linear materials, which essentially translate to small deformations. Of course, the act of eating is anything but a small deformation process, since the whole purpose of chewing is to reduce the size of the primary particles in the ‘solid’ food-stuff such as a wafer biscuit. Large deformation leads first to non-linearity, but then to fracture, which is perhaps one of the least linear processes one could imagine. Hence, any model of the chewing process of a solid-like food has to take into account fracture processes and extreme material non-linearity. It is tempting to think that it is feasible to model this and that one simply requires a sufficiently large computer and some well written Finite Element code, but this is unfortunately far from the truth. There is another, much more serious, underlying problem waiting to ambush the unwary. In fact, the whole problem is almost certainly ill posed, which is very bad news indeed from the perspective of understanding what happens. In mathematical terms, the result here is unlikely to be deterministic, which is another way of saying that the result achieved is overly sensitive to small perturbations in the initial conditions. The consequence of this over sensitivity is that one can usually only determine the probabilities of certain outcomes, rather than expecting the same outcome from every experiment. This of course makes it very hard to compare experiments and models in a simple way that allows us to better understand the mechanics of what is happening. This is not of course to imply that these kinds of simulations are in any way a waste of time; merely to make the observation that it is a very challenging area and that results must be interpreted with care. Beyond this cursory discussion, the rest of this chapter will focus on fluids and will not further discuss solid materials which fracture. The second of the ‘simpler’ cases is that of a Newtonian¹⁰ fluid. When dealing with fluids, we must always consider whether fluid inertia or fluid viscosity are producing the dominant forces. Usually an estimate of these effects is measured by a (dimensionless) quantity called the Reynolds number, which is most simply defined as $Re = \frac{d u \rho}{\mu}$ with d , u , ρ and μ

respectively the characteristic length scale of the flow, the fluid velocity, density and dynamic viscosity. Generally speaking, high Reynolds numbers are bad news from the perspective of obtaining a deterministic result. Looking at the definition of the Reynolds number we can see that large Reynolds numbers equate to low viscosities, large characteristic lengths or high velocities. Water has a viscosity of about 1 mPas, which is very low, such that drinking a glass of water will generate very large Reynolds numbers, particularly during the process of swallowing. The observable consequence of this is that it is almost impossible to exactly repeat the experiment of drinking a glass of water and generate

⁹Classical linear elasticity theory (see for example Timoshenko and Goodier, 1970) was developed for metals, which are only deformable at very high stresses, such that the bulk and shear moduli are of comparable magnitude. This results in significant compressibility, often expressed in terms of the Poisson ratio. For fluids, and ‘soft’ elastic materials, the shear modulus (or viscosity) are many orders of magnitude less than the bulk modulus (or bulk viscosity), and as such they are effectively incompressible.

¹⁰A Newtonian fluid has constant viscosity regardless of history or rate of deformation and is incompressible.

exactly the same flow twice. Hence the problems of high Reynolds number flows are analogous to those of non-linear elasticity and fracture, at least in terms of their having a predictable result.

However, for small Reynolds number processes, equating to either small gaps or high viscosities, there is a well-defined, non-chaotic, hydrodynamical solution, as long as the boundary conditions of the flow are known (and well behaved – more of this later). This means that the flows are repeatable and the problem is well posed which is in marked contrast to the cases we have already discussed. In theory, at least, one could exactly repeat the experience of drinking a sufficiently thick milkshake.

Although it is tempting to try to model the entire mouth cavity, the lack of good knowledge of the exact geometry and dynamical responses of the soft tissues make a full simulation such as this a daunting prospect. Luckily, one can consider smaller, simpler problems such as the squeezing of a mass of fluid between the tongue and soft palate and learn much from their solutions. An additional advantage to solving simpler problems is that there are often closed form analytical solutions available, which give us an exact relationship between all of the variables involved. This is an advantage over solutions obtained numerically (i.e. from a CFD¹¹ package) which require many simulations in order to construct a parametric sensitivity analysis. Of course the payback is that the numerical simulation can deal with considerably greater complexity than a problem that might be analytically tractable. As always, one should adapt the choice of model to the original question to be answered.

So long as the small Reynolds number condition is maintained, one can relax the Newtonian condition and allow for considerable complexity in the functional form of the viscosity and still obtain closed form solutions. In general, the viscosity, which is constant for a Newtonian fluid, can be a function of the local deformation rate, or indeed the deformation rate history experienced by the ‘element’ of fluid. The former and latter cases are discussed in detail in for example (Tanner, 2000; Bird *et al.*, 1989). There are almost as many rheological models as French cheeses, to cover just about every eventuality. Some of these, such as the FENE model, have a physically based derivation and some, such as the so called power-law fluid (Tanner, 2000), are simply curve fits to stress-strain-rate data. Each particular area tends to have its own favourite model, for example Chocolate engineers will tend to use the Casson model (Beckett, 2008).

It is important to realise that even for these complex fluid models, the effects of structure in the material are effectively ignored.¹² As we established in the first part of this chapter, much of the interesting textural information is contained in the structural details of the food under consumption. Deformation of a continuum fluid generates steady or slowly varying stresses, except in some pathological cases of instability, and consequently provides little high frequency information to the mechanoreceptors. If we accept the hypothesis that most of the stimuli for textural interest, at least beyond attributes such as thickness, are generated by high frequency stress/strain fluctuations, then we need to go beyond continuum models in order to understand and predict their origin.

¹¹Computational Fluid Dynamics.

¹²This isn't strictly true, since all non-Newtonian effects can be attributed to structuring at some level. The point I'm trying to make is that the very essence of a continuum theory is smoothness, and as such we are not explicitly accounting for structural features, at least at the level of an individual bubble, drop, particle or whatever. There are a number of advanced theories for materials such as liquid crystals (de Gennes and Prost, 1995), which do have an explicit structural parameter (usually an alignment vector field called the director), but these are beyond the scope of our current discussion, and even they are still not representative of structural inclusions in a resolved manner.

Before we consider the effects of explicit structuring of the continuous phase, we pause to take a look at the boundary conditions at the edge of the fluid domain. The boundary to which we refer is, in reality, almost certainly, one of three things: a contact with a rigid constraint such as a tooth; a biomechanical contact with the tongue or soft palate for example; or a so called 'free surface', which implies contact with a (relatively) inviscid material such as air. In terms of hydrodynamics of the form that is encountered in the current context, we require a boundary condition in terms of the velocity, or its gradient, at the edge of the fluid domain.

The first case, that of a rigid constraint, imposes some condition on the velocity at the boundary, the normal component of which is obviously zero.¹³ The tangential constraint is less obvious, but common practice is to assume a no-slip condition, which imposes that the fluid adjacent to the constraining structure will move parallel to it and at the same speed. The alternative extreme is that of perfect slip, which implies that there is no shear stress at the surface. In the case of biological materials, the surface condition is likely somewhere between the two, since it is by no means a smooth homogeneous material. There is a good discussion of this in Leal (Leal, 2007).

In the second case, of deformable or soft biological constraint, the boundary condition is more likely to be well approximated as a stress condition. Essentially this imposes a constraint on the velocity gradient of the fluid via the viscosity.¹⁴

Free surfaces are a generalisation of the second case, although they are likely to include a contribution from the surface tension, which creates stress in order to resist curvature. (Strictly speaking, surface tension acts to minimise the surface area, but this amounts to the same thing in most cases.)

Further complexity arises due to dynamic wetting phenomena, which are poorly understood even for relatively simple single phase materials.¹⁵ Biological surfaces manage to often be simultaneously hydrophilic and hydrophobic, due to patches of different kinds of materials, when viewed from the perspective of an aliquot of fluid in the mouth, for example 1 cc and above, which makes it rather difficult to define a meaningful contact angle, which is a pre-requisite for application of the existing single phase theory. Further discussion of these phenomena would warrant a chapter all to themselves, so, having peeped into Pandora's box, we will quickly close it again!

While we are in the context of boundary conditions, it seems appropriate to comment a little on the area of lubrication which, if not exactly a boundary effect, certainly occurs near to a boundary. Perhaps the most commonly quoted sensorially related lubrication effects are attributed to the effects of fats and oils. A common belief seems to be that fat/oil will act as a lubricant in the mouth, which enhances the sensation of smoothness, creaminess and the like. Let's consider this idea from a hydrodynamical perspective. First the question of whether the fat/oil will 'wet' the surface of the mouth.

Imagine that the oil cannot wet the surface. In this case, the surface tension of the oil-containing aqueous fluid¹⁶ would cause the oil to form drops and move away from the

¹³ Assuming that the material is impermeable.

¹⁴ Which may be constant in the case of a Newtonian fluid, or a complex function in the more general case.

¹⁵ The so called moving contact line problem is pathological from the perspective of classical fluid mechanics and remains the focus of much debate about how to relieve the stress singularity at the moving contact line, where the apparent shear rate is infinite!

¹⁶ By this I mean the current contents of the mouth, which could be just about anything, but one would imagine that in most cases it would be an aqueous continuous phase containing saliva.

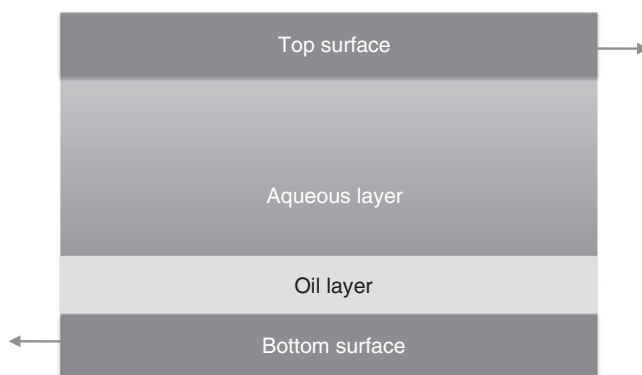


Figure 16.8 Schematic sketch of oil layer close to lower surface under simple shear. The higher viscosity in the oil layer causes the shear rate in the aqueous layer to be higher than if it had occupied the entire gap.

biological surface. In this case, the boundary condition is exactly as it would be for the continuous aqueous fluid without the oil drops, and the oil would not be expected to have a ‘lubricating’ property.

The alternative is that the oil can in fact wet the biological surface and form a film. This is the classical effect that we expect from an oil film in, for example, an internal combustion engine, where the lubricating film reduces the frictional forces by separating the two metal surfaces from contact.¹⁷ However, in the case of a fluid contact, there are no frictional forces and as such this mode of operation is not relevant. As we have seen, slipping, in a hydrodynamical sense, refers to a lack of shear (tangential) stress transmission to a surface. If, as a model, we consider a plate with thin layer of lubricating fluid, and a thicker layer of a second ‘bulk’ fluid on top, we can consider the transmission of tangential stress through the lubricating layer (Figure 16.8). We are interested in deriving a relationship for the relative velocity, u , of the plate-lubricant and plate-bulk fluid interfaces. In the absence of inertia, it turns out that $u = \gamma_0 \frac{d\eta_b}{\eta_L}$ with γ_0 , d , η_b and η_L respectively the prevailing shear

rate in the bulk fluid, the thickness of the lubricating layer, and the bulk and lubricant dynamic viscosities.¹⁸ Hence, if we use the apparent slip velocity as a signature of lubrication we see that any significant lubrication effect requires that $\eta_b \gg \eta_L$. Unfortunately this is certainly not the case for food grade oils such as MCT 260 Pas and water 1mPas! In this sense at least, it seems that fats and oils do not act as lubricants in the way in which we traditionally understand them. Perhaps, then, there might be a mode of lubrication more similar to friction reduction? We will consider this question presently in the following discussion of suspensions, emulsions and foams.

¹⁷The mathematics of this are well described by the classical lubrication approximation solution to the ‘journal bearing problem’. See for example Pnueli and Gutfinger (1997).

¹⁸The more general problem of the evolution of lubricating layer thicknesses sandwiching a bulk fluid between a pair of approaching discs has been studied by Burbidge and Servais (2004). They consider also the dynamically evolving thickness of the lubricating layers, which is itself non-constant in time as it flows.

Box 16.1: Green's functions for the Stokes equation.

$$P = \frac{F_j x_j}{4r^3} + P_\infty$$

$$u_i = \frac{F_j}{8\pi r \eta} \left(\delta_{ij} + \frac{x_i x_j}{r^2} \right)$$

$$\tau_{ij} = \frac{-3F_k}{4\pi} \left(\frac{x_i x_j x_k}{r^5} \right)$$

P is the total hydrostatic pressure at x_i ; P_∞ is the hydrostatic pressure in the absence of the inclusion; u_i is the velocity field at x_i induced by the singular point force F_j positioned at the origin; r is the Euclidian length of the vector x_i ; δ_{ij} is the Kronecker delta; η is the dynamic viscosity of the fluid and τ_{ij} is the deviatoric stress tensor at x_i .

Having extensively discussed the effects of 'simple' fluids, we move on to consider what additional effects we might expect to find when we include dispersed pockets of one material in another. From the perspective of mechanics at least, there is little to distinguish between bubbly liquids,¹⁹ emulsions and (spherical) particulate suspensions. In fact, one can consider the hydrodynamics of this general class of systems as being parameterised by only two dimensionless groups. These are the viscosity ratio of the inner and outer phases, and the capillary number, Ca , which characterises the relative importance of surface tension and the viscosity of the (external) fluid. Once again, the hydrodynamics of such systems has been extensively studied, and closed form analytical results describing the behaviour of single and paired spheres (and other generalised shapes) are available (Kim and Karrila, 1991). Simulations of large collections of spherical inclusions have also been considered in some depth by Brady (Brady and Bossis, 1988) and others.

In crude terms, the presence of an inclusion in a matrix or continuous phase of another material leads to a perturbation of both the stress and strain field around such an inclusion. At distances which are sufficiently far from the inclusion, that is to say more than a few radii, these perturbations are well approximated by the Green's function of the Stokes equation (Box 16.1) acting at the centre of the virtual particle (this is analogous to the solution to the Navier elasticity problem discussed in Section 16.2). Hence, based on these solution building blocks²⁰ one can provide estimates of the apparent perturbative stresses.

We can see from the Green's functions of the Stokes equation (Box 16.1) that the physical properties of the fluid, in this case viscosity, η , only determine the range of the

¹⁹As a distinct case from foams of high gas fraction, in which the bubbles interact strongly and are usually non-spherical.

²⁰In fact it's slightly less straightforward than it sounds since one needs to determine what the singular point force that represents a particle ought to be in terms of the prevailing far field flow. This can be achieved by means of generalised expressions called Faxen's laws, which express this force in terms of the undisturbed far-field flow.

velocity field around the disturbance itself. At first sight this seems odd, but remember, the Stokes equation has no inertia and as such is really a statement of Newton's second law 'force = rate of change of inertia' in which the inertia vanishes. In this context, it is more obvious why only the velocity field is modulated by the viscosity. Although the stress field is independent of viscosity, the strain rate field is inversely proportional to viscosity (because the stress is the product of the viscosity and the strain rate field).

For reasons related to their relative deformabilities, foams and emulsions don't generate such strong perturbations as particles.²¹ An interesting question to ask is: under what conditions the contact between a particle or highly viscous drop might become frictional? From a purely theoretically point of view, one could argue that one could never achieve contact with a finite stress in a finite time, but in reality this is largely irrelevant, since to all intents and purposes a very close contact is enough to observe a transition from a rheological (bulk fluid behaviour) to tribological (generalised frictional behaviour) (Kavehpour and McKinley, 2004). One might advance an argument that invokes the finite deformability of the apparent boundary material in order to explain this behaviour. Essentially, in the case of a non-parallel plate flow (most tribometers use a sphere), the upstream flow generates less normal stress on the interface than the flow near the contact itself. At small enough gaps, this would deform the bounding material, the stylus, or both and consequently, so long as this deformation is asymmetric, there is a component of the normal stress which resolves along the deformed interface, which results in a normal stress dependency and a classical Coulombic type of interaction.

We now briefly return to the subject of viscous oil layers apparently acting as lubricants. Looking at the Green's function for the strain field, we note that the 'range' of the field generated by the point force scales inversely with the viscosity. The effect of this is therefore that a viscous surface layer will transmit lower normal strains than an aqueous sublayer of equivalent thickness. Of course, this is a gross simplification of the complex interactions between a stress/strain source and the presence of a deformable boundary, which is completely ignored in the context of this analysis. However, it seems that a mechanism along these lines might offer some explanation of the apparent 'smoothness' of fatty/oily materials, which is not lubrication in the hydrodynamical sense, but more like a micro-shock absorber.

Stresses are also certainly induced by temperature gradients, which are likely to arise when very hot or very cold foods are eaten, due to contraction/expansion of the biological material in which the mechanoreceptors are embedded. It is not beyond the realms of possibility that concentration gradients of small molecular species may also have a stress inducing effect by means of strong osmotic gradients, although one would expect that these effects would be on a much slower time scale than the thermal effects.

The effects of any phase changes are also worthy of consideration. Since phase changes are characterised by a latent heat, they will always generate temperature gradients, which may be small or large depending on a number of factors such as the volume of the material and the rate of the transition. As mentioned in the previous paragraph, thermal gradients will also generate stresses.

²¹This effect doesn't manifest directly in the Green's functions, but comes in through the generalised Faxen law that is used to determine the force vector acting at the singularity. Strictly speaking, the finite radius of the inclusion requires that the perturbation applied is a full Taylor series of increasingly high order derivatives of the Green's functions shown here. This is known as the multi-pole expansion.

16.4 ENGINEERING OF MICROSTRUCTURES IN FOOD

Classical thermodynamics requires that a system in equilibrium minimises its free energy,²² G , defined according to $G = H - TS$ where H , T and S are the enthalpy, absolute temperature and entropy respectively. Hence the free energy can be viewed as a potential driving the system towards equilibrium. For mixtures, there is always a cost of maintaining an interface between molecules of different species, such that dispersions of dissimilar species have a high energy penalty. This penalty is to some extent compensated for by the gain in entropy of the dispersion, but the entropy contribution is very small unless the size of the dispersion approaches that of the molecule itself.²³ Consequently, thermodynamics requires that all systems evolve towards a molecular scale (dis)organisation. Depending on the temperature, either the enthalpic or entropic terms are dominant resulting in a crystal (organised) or fluid (disorganised) respectively.

As we have seen from the previous discussion of stimuli provided to the mechanoreceptors, the scale of many structures that interest us in terms of textural stimulation are required to be many orders of magnitude larger than molecular. This implies that texturally interesting materials are inherently required to be 'out of equilibrium'. Thermodynamics²⁴ doesn't tell us much about how fast a system will revert to its equilibrium state; only that it will eventually get there!

So, we have two questions to address: first how can we create structures at the length scales we require, and, second, how can we control the rate at which these structures relax to thermodynamic equilibrium?

Classical process engineering is of course based on the foundations of near equilibrium thermodynamics, because, in most cases, the products required are simple commodity chemicals. When you're making sulphuric acid, it doesn't matter how you make it, it is always H_2SO_4 . Therefore, although classical process engineering can tell us a lot about optimisation and general process design considerations, the question of microstructure is pretty much out of scope. Essentially we need to provide, and hopefully control, a mechanism to arrest, or at least significantly reduce the rate of structural degradation due to the underlying thermodynamic potentials.

Based on these arguments, we conclude that any process that yields a structured product (with a reasonable lifetime), requires a careful balance between kinetic structuring processes such as droplet breakup and a kinetic quenching or arrest. In most cases these are two, nominally separate, and ideally sequential, steps. In reality, however, there is always a degree of interaction. In broad terms, the structuring processes require energy input, hopefully in a controlled manner; the arrest is usually achieved by some kind of bulk rheological transition, be it gelation, thickening or a glass transition. Potentially one could imagine a surface stabilisation also, via some kind of surface phase transition, or surface active materials.

²²This is the Gibbs free energy, which for an incompressible material is functionally identical to the Helmholtz free energy, in which the enthalpy is replaced by the internal energy, U . Since most of the systems that we are dealing with are more or less incompressible, the distinction is unimportant. As the change in free energy between states is all that matters, the distinction could be important for foamed materials with large pressure swings.

²³The entropy is proportional to the log of the number density, so the molecular contribution will almost always win.

²⁴We can imply something from statistical mechanics, but only for very simple systems, so that doesn't help much either.

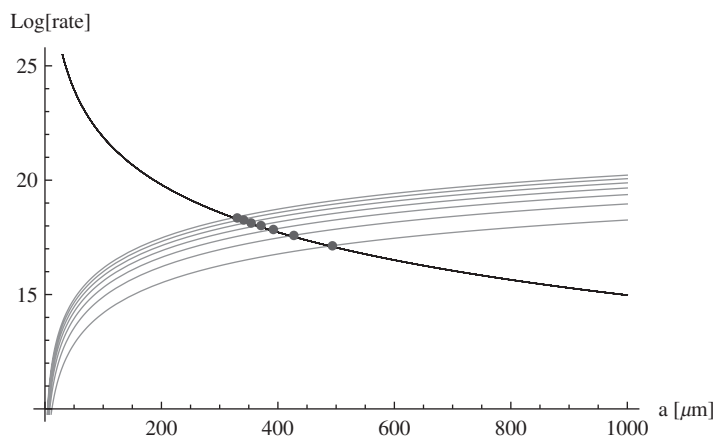


Figure 16.9 Predicted rates of breakup (lower curves) and coalescence (upper curve) for simple emulsification model for a range of power inputs. Steady operating point of the emulsifier is predicted to be the intersection of the two curves which are marked by the solid circles. Rates are given by

$$rb = \frac{1.6a(P - \dot{\gamma}^2) \left(1 - \exp\left(\frac{-a\eta}{\sigma}\right) \right)}{\sigma\phi} \quad \text{and} \quad rc = \frac{\dot{\gamma}P_c\phi^2}{4\pi a^3}$$
 with a , P , $\dot{\gamma}$, η , σ , ϕ and P_c respectively the droplet radius, power input, shear rate, dynamic viscosity, interfacial tension, volume fraction of dispersed phase and collision effectiveness. Equations quoted here were derived by the author based on the kinds of scaling arguments detailed in the text.

As a first example we consider the emulsification or foaming process. Here one seeks to disperse drops of one phase (the discrete phase) in a second continuous phase. For example, oil in water and water in oil emulsions are both achievable and observable on reasonable time scales.²⁵ In commercial equipment, this energy input is usually achieved by means of some kind of high speed rotor/stator assembly. An important characteristic is the smallness of the gaps, and this need is driven by the viscosity ratio of the two phases. It is very hard to transmit shearing energy into low viscosity fluids,²⁶ hence the small gap reduces the inhomogeneity of the flow.

Nevertheless, in practice we find that the emulsion droplet size produced by rotor/stator devices is apparently limited, in the sense that the energy required to make increasingly small drops/bubbles increases much faster than the drop/bubble size is reduced (Figures 16.9 and 16.10). Why is this? A number of phenomena contribute to this, but perhaps the most significant is coalescence of the droplets. This is a process which is easiest to understand from a statistical mechanical perspective. In this frame, we define a probability of droplet pair collision, a base time scale (inverse rate), and a collision efficiency. Once this ‘collision kernel’ is known, one can appeal to the mass balance and write what, in engineering, is called a population balance equation. The exact form of this is not important to the

²⁵Conceptually one could disperse anything in anything else for a short time provided enough energy was supplied in an appropriate form. One example of an uncommon emulsion is a cloud – a water in air emulsion or aerosol. The apparent stability of clouds over long periods is a very interesting subject, involving thermal convection effects which are beyond the scope of the current chapter!

²⁶One common way to consider the physical definition of viscosity is to draw analogies between heat/mass transfer and fluid mechanics. In this ‘transport phenomena’, view, the viscosity is the analogous property to thermal and molecular diffusivity, and as such can be seen as ‘diffusivity of momentum’.

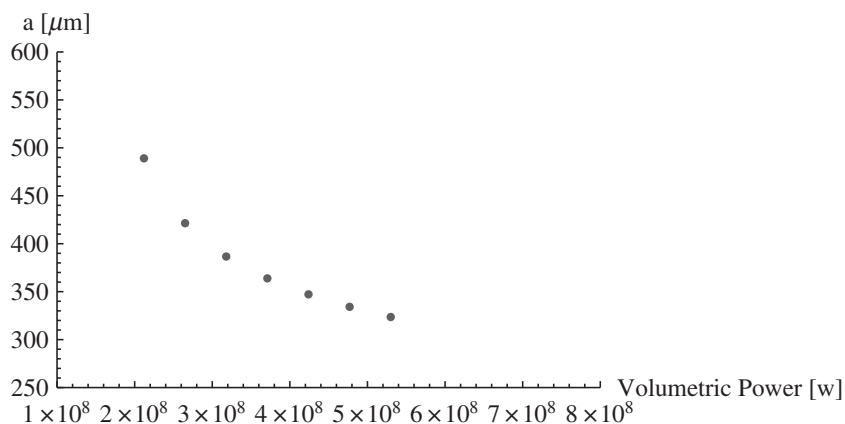


Figure 16.10 Predicted droplet size as a function of power input for the model emulsifier described in Figure 16.9. Note that reducing the droplet size requires increasing large increments in energy input due to the effects of coalescence.

current discussion beyond noting that the probability of droplet collision is a modified cross-correlation function which scales as the square of the number density of droplets.²⁷ Now we can see the reason that adding more energy is a law of diminishing returns, since even though we break more droplets, the rate of coalescence increases very quickly. The only obvious way to avoid this is to reduce the collision probability by reducing the concentration of the dispersed phase. The penalty that this imposes is that the efficiency is very quickly reduced since lots of energy is dissipated in the ‘extra’ continuous phase; the final emulsion/foam thus produced must also be concentrated in a post-production step. Since the gas phase is compressible, there is one other trick available for foams. One can, in principle, manipulate the relative volume and number concentrations of the bubbles, and hence to some extent the breakup and coalescence rates by means of the prevailing pressure.

Once a foam or emulsion is produced, there are various mechanisms of instability that can cause it collapse or coarsen. Most of these relate to bubble–bubble or drop–drop contacts, but we must also consider Ostwald ripening, which requires no bulk mobility or deformation.

Avoidance of bubble–bubble or drop–drop contacts can be achieved either by acting on the hydrodynamics, or by charge effects.²⁸ As discussed in Section 16.3, one can alter the prevailing hydrodynamic behaviour either through the bulk rheology, or by changing the boundary conditions. For most emulsions and wet foams, the manipulation is at the level of the boundary condition by means of surface active agents. There is a significant confusion surrounding the use of surface active agents to stabilise foams, one reason being that people rarely define sufficiently clearly what they mean by ‘stable’. Undoubtedly, there are many subtle and complex effects that are influenced by surfactants, but in the current

²⁷This is a gross simplification, since the collision cross-section also matters along with a lot of other factors such as randomness of the flow etc. However, the basic conclusion, that as the droplets get smaller the collision rate increases rapidly, is valid despite the simplification.

²⁸If the drops or bubbles are very small ($< 1 \mu\text{m}$) then one can use classical approaches from colloid science – see for example Hunter and White (1987).

context we define stability as the inverse rate at which bubble or drop pairs can approach one another.²⁹ This is somewhat related to ‘drainage’ and ‘creaming’ in the loose, prevailing viewpoint. Given our definition, one can approximate the region of fluid between two bubbles as an approximate squeeze flow between a pair of plates. The advantage of this situation is that we know the solution to this problem (Engmann *et al.*, 2005), which tells us that the boundary condition at the plate (which represents the bubble or drop surface) has a very strong effect in determining the rate at which the film thins. Clean interfaces cannot support shear stress and as such are analogous to a slip boundary condition; interfaces covered in surface active species support shear stress gradients by means of Marangoni effects, and as such are analogous to partial slip or complete immobility depending on the concentration and other properties of the adsorbed surface active entities. For fixed force, slipping interfaces can approach much faster than partially or totally immobile ones, with the consequence that surface active species should slow down bubble/drop collision and hence coalescence rates. A common misconception is that surface active agents act to reduce the surface tension of the interface, which stabilises bubbles/drops against coalescence. As we can see, we should expect surface active agents to reduce the coalescence (and Ostwald ripening) rates of foams and emulsions, but for coalescence this has nothing to do with the surface tension.

Ostwald ripening or disproportionation is driven by differences in the internal pressure (Laplace pressure) of bubbles or drops of different sizes, which arise due to the effects of surface tension and curvature. Gas or liquid is therefore driven out of the bubble/drop into bulk solution, and then redistributes, most often predominantly to the headspace (which can be viewed as an infinite bubble with no curvature). The net observable effect is then that small bubbles get smaller and big bubbles get bigger over time. Based on this explanation, one can propose several strategies to reduce the rate of ripening. If one reduces the surface tension by means of a surface active species, then the Laplace pressure differences and hence the rates of transport are reduced. Alternatively, if the gas is substantially insoluble in the continuous phase, then the net effect is the same as adding a surfactant. One could also try to reduce the poly-dispersity of the sample, which again would reduce the coarsening rate. It is often argued that a perfectly mono-disperse foam or emulsion should be stable against Ostwald ripening, but this neglects the natural fluctuations present in any system, and the inherent instability of the system to any perturbation of the size distribution. Realistically one would expect that a near mono-disperse size distribution might result in a lag or lead time, rather than a permanent slowing of the ripening process.

We now consider some specific processes and discuss the application of these principles.

16.4.1 Freeze drying

Perhaps one of the simplest methods of preserving structure is freeze drying, which is commonly used for many food products, in particular instant coffee powders and fruit pieces for breakfast cereals. Freeze drying, as with all of these examples, relies on competition between two processes with disparate time scales, a structuring and a relaxation process. The structuring process here is the removal of frozen water phase by sublimation;

²⁹To be completely clear we should specify that the bubbles are not so close together that the film between them is very thin. This excludes Newton black films, disjoining pressures etc., all of which are extremely important close to film rupture. I would include all of these effects in ‘collision efficiency’ rather than ‘collision rate’.

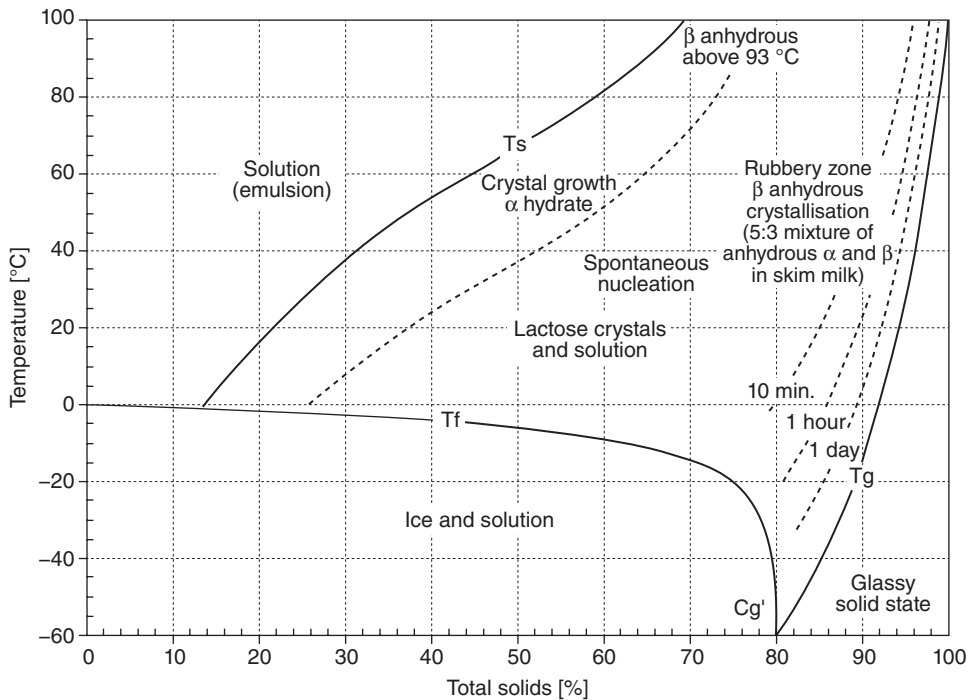


Figure 16.11 State diagram for whole milk – after Vuataz (2002).

the relaxation process is the collapse of the porous matrix. The relaxation process is driven by the surface tension of the new surface created, which collapses the structure at a rate determined by the prevailing viscosity of the material. The effect of the freezing is twofold. First, the viscosity of ice is significantly greater than that of water, such that the rate of the structural collapse is reduced. Second, the fact that the conditions are chosen such that the ice sublimates means that there is no liquid meniscus and hence no surface tension-driven driving force.

A useful tool for considering these kinds of processes is a so called state diagram, a typical example of which is presented in Figure 16.11. Although this particular example is for whole milk, the general form of these diagrams is more or less similar for many materials of interest to us. In brief, there are four regions, which are delineated by four transitions. The top left corner represents a single phase solution, the liquid phase, which is bounded in temperature by the freezing curve, T_f , and in concentration by the solubility line, T_s .³⁰ Below the freezing point, the solution is metastable and will eventually phase separate into a mixture of crystals and concentrated solution. The freezing curve illustrates the colligative effect of freezing point depression at higher concentrations of solute, which is due to the entropy of mixing. To the right of the solubility curve and above the freezing curve we have a mixture of lactose crystals and an increasingly concentrated solution phase. As we move to higher and higher concentrations, the viscosity of the continuous liquid phase

³⁰In this case we are considering the solubility of lactose, but the concept is valid for any material that forms a crystalline phase.

increases more and more until we eventually reach the glass transition curve, T_g , at which point the molecular motions become severely arrested and the material behaves as an amorphous solid, or glass.³¹ Diagrams such as these provide very useful tools for process design, both from a conceptual and, if hard data is available, numerical process engineering perspective. Unfortunately, there is an enormous amount of careful experimental work required to construct a reliable diagram such as this, and, consequently, there is little data freely available in the public domain. It is also important to realise, however, that there is a lot of information that is not contained in the state diagram. For example, the regions close to the transitions are metastable, with the 'rate'³² of the phase change strongly related to the depth of the quench. Consequently, the size distribution of crystals or inclusions is not represented within the diagram, at least beyond the general rule of thumb that deep quenches lead to fast nucleation rates, and thus large numbers of small crystals when compared to shallow quenches.

We can now realise that, in fact, the reality of the freeze drying situation is considerably less black and white than I have just described. Imagine that we 'plot' the progress of a hypothetical freeze drying process on the supplemented state diagram. Let's say that we take a solution of 10% total solids at room temperature (e.g. 20°C). We now cool this solution to -50°C, which causes the majority of the water to freeze, cryo-concentrating the remaining solute to about 80% total solids since the phase separation must eventually reach the freezing curve.³³ If we now dry the sample, by reducing the pressure, then the solution phase will continue to concentrate as liquid water is removed, passing briefly through the rubbery region until it hits the glass transition and the whole thing jams up and the structural collapse is arrested. During this phase of the process, one can continue to drive off the frozen water that forms the ice crystals until the ice crystals are completely removed. If we now keep the pressure at a reduced level, we can now slowly raise the temperature and move up the glass transition, T_g , curve (or at least an isoviscosity line close to it) until we reach ambient temperature. Once at ambient temperature, the pressure can be returned to ambient and we have a porous self stable powder, with the pore structure templated by the (sublimed) ice crystals created in the initial freezing step.

If one is familiar with the classical physical chemistry of phase diagrams and transitions, one might be tempted to ask whether the concept of tie-lines can be applied to determine the mass balance of the process and the relative fractions of the various phases. In principle the answer is yes, but only when the axes used represent quantities of pure materials. In systems as complicated as foods, this condition is rarely, if ever, met for a number of reasons (e.g. unknown M_w of natural materials, sheer number of component molecules etc.).

16.4.2 Puffed cereals

Puffed cereals are generally produced by an extrusion process. Usually the cereal paste is mixed, and cooked in the extruder barrel. The final part of the barrel is the essential part of the process, in which the paste is superheated under a back pressure due to the flow

³¹ Depending on the size of the molecule, not all of the modes are necessarily arrested at the T_g . For example long chain, flexible polymers.

³² In this context, rate, refers to the nucleation rate, which combines with the growth rate of existing lumps to determine the evolution of the size distribution.

³³ It may take a long time to get here, since the viscosity of the liquid phase is continuously increasing!

through the die. The superheated material is stable so long as the pressure is maintained, but, once the pressure is released as the material passes through the die, the mixture becomes metastable, and the steam ‘flashes off’. As the flash occurs, there is a phase separation into a steam phase, the quantity of which is determined by the degree of superheating through the heat balance, and a concentrated cereal phase. As the steam nucleates in the cereal structure, it rapidly expands, taking the cereal material with it and forming a foamed structure. As the generation of steam removes water from the starchy cereal material, it is effectively dried until it becomes sufficiently concentrated to undergo a glass transition, freezing the puffed structure into a crunchy snack. Once again there is a competition between a structuring (puffing and drying) and a relaxation (structural collapse once the steam has gone) process. The key control parameters in the process are the degree of superheating, the die pressure drop (which is itself a strong function of flow rate), and the rheology of the cereal paste.

16.4.3 Spray dried powders

Spray drying is another very common process in the food industry and is used to produce a huge variety of beverage and other powders (e.g. skimmed milk, coffee, soups, creamers, milkshakes etc). It is a fast process, and can have a very high throughput, although towers often need to be very tall, so are very expensive from a capital perspective.

The spray drying process is once again a competition between several simultaneous processes, the most important of which are droplet breakup, coalescence and mass transfer. The liquid to be dried is pumped into a nozzle assembly at the top of the tower such that a stream of droplets is formed. This is a complex process, which can be controlled by means of energy input, nozzle design and so on. The hydrodynamics are complex, particularly since, in most cases, the throughput is high enough that the breakup is an inertial process, tending to lead to large droplet size distributions. In principle at least, it is possible to run at much lower flow rates and exploit well characterised hydrodynamical instabilities to generate much more controlled droplet size distributions, although it is unlikely to be economical to do so.

Once generated, the droplet stream is entrained in a fast flowing stream of hot air, which provides the energy to remove the water from the droplets. Small droplets will quickly reach the speed of the surrounding airstream and be convected along with the prevailing airstream, which is positive from the perspective of avoiding drop collision and subsequent coalescence, but negative from a mass and heat transfer perspective. Drag from the surrounding gas phase is also beneficial from the hydrodynamical viewpoint, since it generates a recirculation flow inside the drying droplet, which convects the wetter material from the drop centre to the surface, hence promoting a more even drying and less fine generation through reduction of the differential drying stresses.

Spray drying does not inherently generate much structure, but is a good way of preserving previously generated structure, for example an emulsion, assuming that the structure to be dried is not destroyed by the passage through the nozzles.³⁴ Again we have the balance of rates between the droplet collision/coalescence (relaxation) rate and the drying (structuring) rate.

³⁴There is much proprietary technology in the design of nozzles and inlets that try to preserve a certain structure.

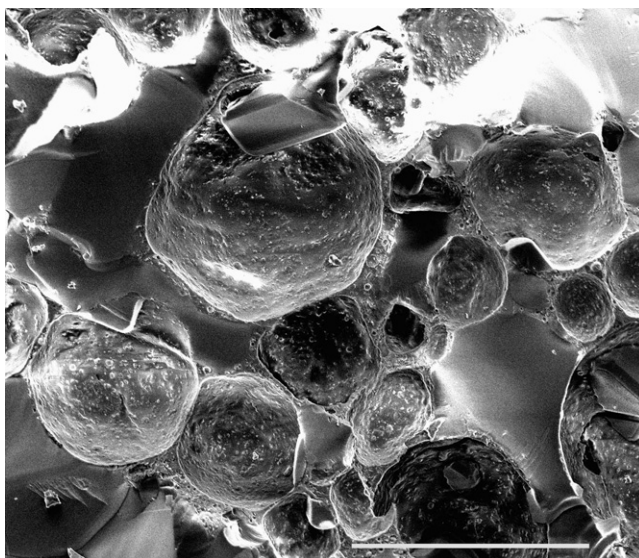


Figure 16.12 Scanning electron micrograph of a typical ice cream sample. Scale bar is 50 μm . Reproduced with permission from Martine Rouvet and Hans-Joerg Limbach.

16.4.4 Ice cream production

The final example that we consider is the production of ice cream (Figure 16.12). This is the most complex of the examples that we have discussed, since it is simultaneously a foam, a suspension (of solid ice crystals) and an emulsion. Depending on process and storage, the air fraction is about 50% by volume, with a mean bubble diameter of the order of about 40 μm . The fat droplets in ice cream are of the order of about 10 μm mean diameter and the ice crystals are typically of the order 20 μm , but will coarsen significantly with aging. Proportions of fat, sugar, milk and so on are very variable between recipes.

Typically the first stage of ice cream production is the mixing of the ingredients to form a wet dairy solution, which is then pasteurised and homogenised in order to reduce the size of the fat droplets and avoid creaming. The next stage is to hold the homogenised liquid phase in a tank for a number of hours to allow the fat to partially coalesce. Since the homogenised fat droplets are actually partially covered with damaged milk fat globule membrane (MFGM), the droplets tend to aggregate and form chains and branched network structures, which have a considerable effect on the bulk rheology of the mixture. Since the MFGM effectively arrests the aggregation process as the fraction of uncovered free surface reduces, the hold time in the tank is not that critical, as long as it's long enough. This convenient decoupling of the kinetics from the structuring process is achieved by the pre-structuring (distribution) of the MFGM between the droplets, which presumably creates a relatively deep local minimum in the energy landscape such that there is a kind of local equilibrium achieved.³⁵ Hence, we have a kind of macroscopic self-assembling³⁶ emulsion gel, which can be broken and will spontaneously reform so long as the energy input is not too large.

³⁵ Actually it's not a true equilibrium, since the global free energy of the system is not minimised, but it results in a fairly predictable state from any starting point within the range of attraction of the local minimum.

³⁶ It's macroscopic with respect to molecularly self-assembling systems, such as amphiphilic polymers.

Having created the template for the small microstructure, we can move to the next stage of the process, which forms the rest of the structure. Generally this is a scraped surface heat exchanger, which simultaneously freezes and shears the liquid material. As the material cools it will nucleate ice crystals, but, since the sub-cooling is relatively shallow, the growth of existing crystals will be faster than the nucleation rate. We would therefore expect that the ice crystal distribution would be dominated by large crystals, except that the shearing of the scraper will break crystals and (probably) enhance the nucleation rate. Consequently, the ice crystal sizes that we observe in freshly made ice cream are quite small, resulting in a smooth texture. The cryo-concentration of the liquid phase as the water is partitioned into the growing ice phase eventually stops the freezing of the remaining liquid phase, such that there will always remain a certain unfrozen fraction.³⁷

Since the freezing/cryo-concentrating ice cream mixture is getting more and more viscous as the process continues, air will become entrained in the mixture. The air inclusions are metastable, since the surface tension of the interface drives the phase separation towards the formation of a single bubble. As previously discussed, the rate of this collapse is modulated by the bulk phase viscosity, which sets a time scale of τ_b which is order $\sigma/\eta a$, where σ , η and a are respectively the interfacial tension, bulk viscosity of the liquid part of the mixture and radius of the air bubble. The shearing process will convect any air pockets in an affine manner, which will eventually cause the bubbles to break up when the Peclet number (the ratio between the convective time scale $\frac{1}{\dot{\gamma}}$ and τ_b is greater than unity. Eventually the bulk ice cream will likely develop a yield stress, which may further stabilise the structure.

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³⁷Eventually the cryo-concentrated phase will undergo a glass transition, at which point the freezing is physically arrested since the water molecules are no longer as mobile in the amorphous matrix. Typically this transition is around -40°C .

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Plate 9.1 Visualisation of taste papillae (the raised dots) using blue food dye.



Plate 9.2 Dental plate with embedded electrodes to monitor salt and pH during eating. The four wire loops attach the plate around the teeth; the plate rests on the upper palate and wires from the electrodes (not visible) are led out of the side of the mouth.

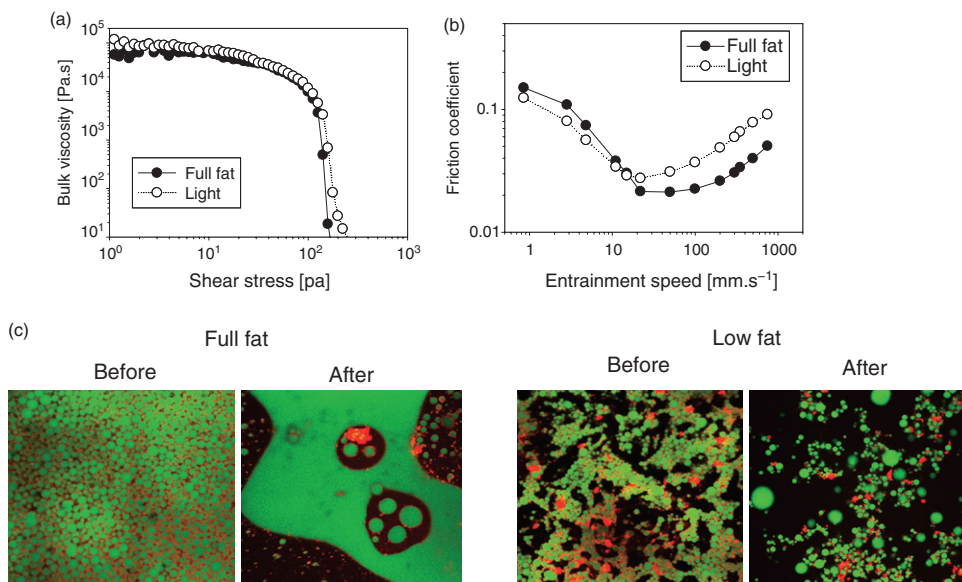


Plate 9.3 Bulk rheological (a) and tribological (b) measurement of full and low fat (light) mayonnaise and (c) confocal microscopy of the structures before and after processing in a rubbing contact, green indicates fat, red protein. From unpublished data from Bongaerts, Houston and Stokes reproduced with permission.

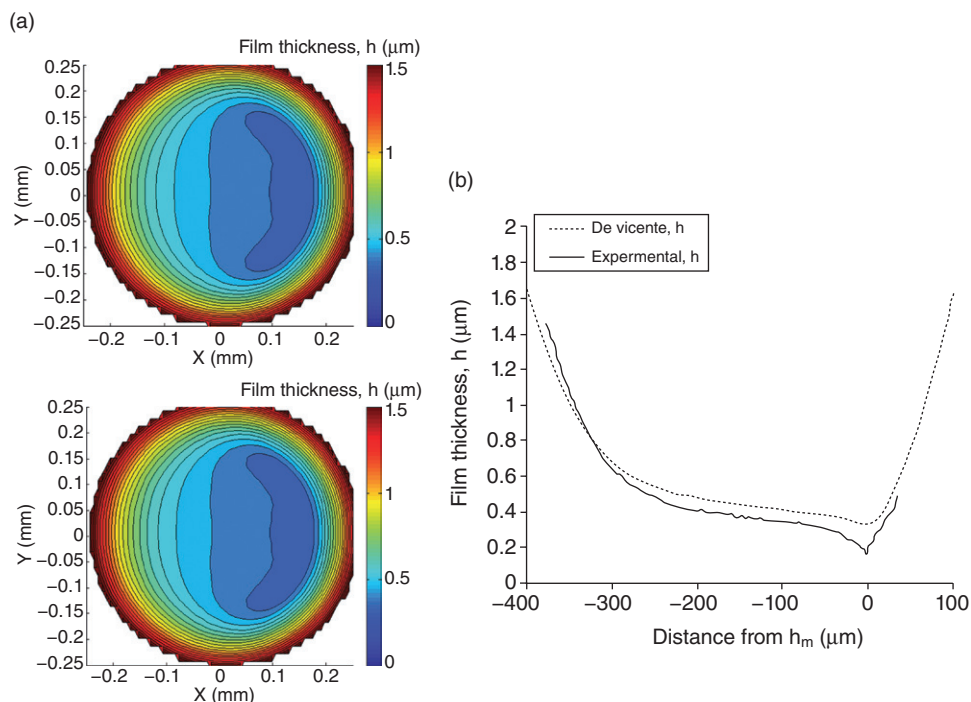


Plate 12.1 Experimental optical interferometry measurements in the elastohydrodynamic regime between a PDMS-coated ball and glass disk at load of 3 mN and speed $U = 0.66 \text{ mm/s}$ in comparison to model predictions of (de Vicente et al., 2005a) lubricated with sunflower oil, showing (a) film thickness map expressed as RGB intensity values indicated in the colour bar, and (b) film thickness profile along centreline. Reproduced from Myant et al., 2010, with permission of Taylor and Francis.